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Implementation of New Damage Stability Regulations in the Design of Small Polar Cruise Ships

Thesis submitted in partial fulfilment of the requirement for the degree of Master of Science in Technology

Espoo 29.6.2018
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Tiivistelmä

Vauriovakavuussäännöt laivoille kehittyvät jatkuvasti. Muun muassa muuttuvat operointiprofiilit ja uudet tutkimustulokset pakottavat Kansainvälisen merenkulkujärjestön IMO:n kehittämään uusia vauriovakavuussääntöjä.

Euroopan meriturvallisuusviranomainen EMSA totesi vuoden 2008 tutkimusprojektissaan SOLAS 2009 vauriovakavuussäännöt puutteellisiksi, jonka johdosta IMO aloitti kehitysprosessin näiden sääntöjen parantamiseksi. Useita ehdotuksia sääntöjen kehittämiseksi esitettiin. Vuonna 2017 SOLAS 2020:nä tunnettu sääntömuutos vauriovakavuuteen hyväksyttiin, ja se astuu voimaan vuonna 2020. Päämuutos säännöissä on uusi laskutapa vaaditulle osastointi-indeksi R:lle.

Lisääntynyt merenkulku polaarisissa vesissä on aiheuttanut tarpeen näillä alueilla operoiviin laivoihin keskittyvään säännöstöön. Onnettomuuksista selviämisen kannalta tärkeitä ovat vauriovakavuussäännöt, jotka ottavat jäävauriot huomioon. Vuonna 2014 hyväksytty Polarkoodi astui voimaan vuonna 2017. Polarkoodi asettaa lisävaatimuksia polaarisissa vesissä operoiville aluksille, mukaan lukien vauriovakavuussäännöt uusille laivoille.

Tämä diplomityö tutkii Polarkoodin ja SOLAS 2020:n vauriovakavuussääntöjen yhteisvaikutuksia pienten risteilijäalusten suunnittelussa. Tarkoituksena on selittää näiden sääntöjen taustaa sekä analysoida niiden vaikutuksia esimerkkilaivan avulla. Tavoitteena on selvittää, mitä valintoja tulee tehdä suunniteltaessa pientä risteilijäalusta, joka noudattaa molempia säännöstöjä.

Työn tuloksena selvisi, että paras ratkaisu uusien vauriovakavuussääntöjen kannalta on cross-flooding -putkien hyödyntäminen. Tämän lisäksi vähäinen osastoinnin lisääminen toimii paikallisten vakavuusongelmien ratkaisussa. Huomattiin myös, että SOLAS 2020 vauriovakavuussäännöt ovat rajoittavampia suunnittelun kannalta kuin Polarkoodin säännöt.

Avainsanat Polarkoodi, SOLAS 2020, vauriovakavuus, jäävaurio, matkustajalaiva

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Abstract of master's thesis

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Abstract

Damage stability regulations for ships are constantly evolving. Changing operational profiles and results from new research, amongst others, force International Maritime Organization IMO to develop new regulations for damage stability.

After a research project conducted by European Maritime Safety Agency EMSA in 2008 found SOLAS 2009 damage stability rules lacking, IMO started a development process to improve the damage stability regulations. Several proposals on how to improve the regulations were presented. In 2017, a new set of damage stability regulations known as SOLAS 2020 was adopted and will enter into force in 2020. The main difference in the regulations is new formulas for calculating required subdivision index R.

The increased amount of marine traffic in polar waters has caused a need for regulations, which focus on ships operating in these areas. Taking ice damages into account in these regulations is important for survivability. Polar Code, adopted in 2014, entered into force in 2017. It sets additional requirements for ships operating in polar waters, including damage stability regulations for new-built ships.

This thesis studies the combined effect of the damage stability regulations of Polar Code and SOLAS 2020 in the design of cruise ships. The aim of this thesis is to explain the background of these regulations and analyse the effect of them with an example case. The purpose is to find, what design choices are required to design a small cruise ship, which can comply with both sets of regulations.

As a result, it was found that utilizing cross-flooding pipes is the best solution in regards to the new damage stability regulations. In addition to that, slight addition of subdivision works at the solving of local stability problems. It was also noticed that SOLAS 2020 damage stability regulations are more restrictive for design than those of Polar Code.

Keywords Polar Code, SOLAS 2020, damage stability, ice damage, cruise ship

Foreword

This Master's Thesis studies the newly adopted SOLAS 2020 and the newly released Polar Code. As they set new safety criteria for ships and have not been studied widely, the topic was of interest for me and offered and opportunity to familiarize myself with the new rules. The thesis was made in contract with Arctech Helsinki Shipyard Inc. during Spring 2018.

I would like to thank my advisor Mr. Eero Kareoja for his good advice in all the different stages of writing the thesis. I am also grateful to my supervisor Professor Pentti Kujala for all his help, especially for guiding me to find an academically interesting angle for this thesis.

I would also like to thank Ms. Heini Kiuru for her immense help in everything regarding the case ship. My other colleagues at the Project and Theory -department of Arctech also deserve thanks for all their help and support. Gratitude belongs also to Arctech Helsinki Shipyard Inc. for its financial support, which enabled me to write this thesis.

Finally, I would like to thank my sister Laura for proof-reading my thesis and making sure it is readable.

Espoo 29.6.2018

Jaana Haussalo

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Acronyms

A		Attained subdivision index
B	[m]	Breadth of the ship
BM	[m]	Metacentric radius
d_s	[m]	Deepest subdivision draught
d_p	[m]	Partial subdivision draught
d_l	[m]	Lightest subdivision draught
GM	[m]	Metacentric height
GZ	[m]	Righting arm lever
i		Index of compartment or group of compartments considered
I_T	[m^4]	Moment of inertia of the waterplane
K		Constant used in calculation of s_i, depends on ship type and θ_e
KM	[m]	Height of the center of buoyancy
KG	[m]	Height of the center of gravity
L	[m]	Length of the ship
M		Metacenter
M_{st}	[$kg*m^2/s^2$]	Righting moment
M_{ulk}	[$kg*m^2/s^2$]	External moment
N		Number of people on board
p_i		Probability, that i may be flooded
R		Required subdivision index
Range	[degrees]	Range of positive righting lever
s_i		Probability of survival after flooding i
T	[m]	Draught of the ship
VCG	[m]	Vertical center of gravity
W	[ton]	Weight of the ship
Δ	[ton]	Displacement
	[$kg*m/s^2$]	Buoyancy vector
θ_e	[degrees]	Equilibrium heel angle in any stage of flooding
θ_v	[degrees]	The angle, where the righting level becomes negative
ϕ	[degrees]	Angle of inclination
∇	[m^3]	Volume of displacement

Abbreviations

BMVI	Federal Ministry of Transport and Digital Infrastructure (Germany)
COLREG	International Regulations for Preventing Collisions at Sea
EMSA	European Maritime Safety Agency
EU	European Union
FCS	Flooding Containment System
FSA	Formal Safety Assessment
GOLADS	Goal-based Damage Stability
ICLL	International Convention on Load Lines
IMCO	Intergovernmental Maritime Consultative Organization
IMO	International Maritime Organization
IS 2008	Intact Stability Code, 2008
MARPOL	International Convention for the Prevention of Pollution from Ships (marine pollution)
MDO	Marine Diesel Oil
MES	Marine evacuation system
MSC	Maritime Safety Committee
R&D	Research and development
RoPax	Ro-Ro passenger vessel
SDC	Sub-committee on ship design and construction
SOLAS	International Convention for the Safety of Life at Sea
SPI	Survivability Performance Index
UIWL	Upper ice waterline length
UN	United Nations

1 Introduction

1.1 Cruise ships

A cruise ship is a type of passenger ship, which is used for pleasure voyages, where on-board amenities and activities may be more important than transportation. Passenger ships concentrated on transportation are called ocean liners. Ocean liners are passenger ships, which are dedicated to transporting passengers from one point to another rather than doing round trips like cruise ships. However, the distinction between cruise ships and ocean liners has blurred in terms of operation profile. Larger cruise ships may operate like ocean liners, taking longer trips which may last even months. The differences can be found in terms of construction. Ocean liners are built to withstand rougher sea conditions by having for example higher freeboard and stronger plating.

In this thesis, the term "cruise ship" is used to describe both cruise ships and ocean liners. The term "cruise ship" rather than "passenger ship" is used to exclude RoPax vessels, another type of passenger ship. This exclusion is made, because the damage cases of RoPax vessels differ from those of cruise ships. For example, the issue of water-on-deck is only applicable to RoPax vessels. Also, the damage stability calculation according to SOLAS 2020 rules are slightly different for RoPax and cruise ships. Ferries and narrowboats are not included to the definition of "cruise ship" in this thesis either. Ferries and narrowboats are types of passenger ship, which tend to be used in inland waterways and may often not comply with SOLAS regulations.

There is a lot of variation within the cruise ship -group. The smallest cruise ships have only a few passengers, but those are quite uncommon and also do not need to comply with SOLAS regulations. Nowadays, the largest cruise ships are hundreds of meters long with capacity for thousands of passengers.

1.2 Background

The first damage stability regulations for ships were adopted in 1914 in response to the concerns raised by the sinking of *Titanic* in 1912. These regulations were a part of a convention aiming to improve the safety of sea faring. The convention was named the International Convention for the Safety of Life at Sea (SOLAS). SOLAS has been developed and updated over the years, first through new conventions, nowadays through amendments and is upheld by the International Maritime Organization (IMO). The currently effective damage stability regulations are found in SOLAS 2009. In SOLAS 2009 chapter II-1 the safety level of passenger ships regarding stability is determined by the R-index, which depends on the length of the ship and the number of passengers on-board. The safety level is considered to be sufficient if the A-index, which is calculated for the watertight subdivision, is greater than the R-index.

Even before SOLAS 2009 damage stability regulations entered into force, concerns were raised, whether the regulations set the safety level requirements high enough. Numerous research projects were conducted and they found SOLAS 2009 lacking and the decision was made to revise safety standard. Also, the 2012 accident of *Costa Concordia* contributed for the concerns about whether the safety needs to be raised after flooding. The results of the research projects together with the accident led to revision of SOLAS II-1.

SOLAS regulates the safety of sea faring in open waters, which at its conception in 1914 was sufficient. However, nowadays there is need for regulations for ships travelling in polar waters. Transporting cargo through Northeast Passage or taking scenic cruises in the Antarctic waters are of this day. In the same way as *Titanic* and *Costa Concordia* have affected SOLAS regulations, such accidents as e.g. *MV Explorer* contributed to deciding that regulation in polar waters was needed. Regulations which take into consideration ice and other polar water conditions, were adopted in 2014 by IMO.

The International Code for Ships Operating in Polar Waters (Polar Code) entered into force in 2017. Also in 2017, new damage stability regulation amendments for SOLAS were agreed upon and will enter into force in 2020 (SOLAS 2020). SOLAS 2020 damage stability regulations introduce new R-index for passenger ships, which for ships with less than 400 people on board is a constant 0.722. In Polar Code, the damage stability regulations concern the survivability index and the extent of damage caused by ice. If a cruise ship operating in polar waters is going to be designed, it needs to comply with both SOLAS and Polar Code.

1.3 Research problem, goal and scope

Polar Code is a relatively new regime, having entered into force in January 2017. SOLAS 2020 amended damage stability regulation was only adopted in June 2017 and will enter into force in two years' time. Both sets of regulations are quite new and therefore there has not yet been documents or guidelines published concerning the effect of these regulations on design. Also, there has not yet been ships built complying to both of these sets of rules, which would have gone through the class approval process. The lack of precedent cases makes it relevant to study the combined effects of the damage stability regulations of Polar Code and SOLAS 2020 on design. Limiting the study to small cruise ships is of interest, because for them, the R-index is constant, which is a significant change from previous regulations and the change in the R-index is bigger than for ships with more passengers. Also, because subdivision for small ships is already challenging, examining the effect of the added restrictions of Polar Code is worthwhile.

The literary part of this thesis gives an overview of the stability of ships as a physical phenomenon with emphasis on damage stability and reviews the solutions for improving the damage stability and survivability of a vessel in damaged state. Also, the development of damage stability regulations in SOLAS and Polar Code is examined, including the research projects conducted to find the new R-index for SOLAS 2020.

The experimental part of the study is carried out as a case study. The purpose of the case study is to examine how the new damage stability regulations of SOLAS 2020 can be combined with the damage stability regulations of Polar Code in the case of small cruise ships. "Cruise ship" is defined in chapter 1.1 of this thesis. In this study, a "small" cruise ship means a cruise ship with less than 400 people on board, but which still is considered passenger ship under the SOLAS regulation (more than 36 people on board).

The study of a vessel's damage stability is limited to the examination of SOLAS II-1 part B1 with the amendments approved in MSC 98 and to subchapter 4.3.2 of Polar Code. International Convention of Load Lines (ICCL 66/68) and Intact Stability Code 2008 (IS 2008), which must be taken into account in the design of passenger ships, are not examined in this study. The concept ship of the case study is designed to fulfil the requirements of the aforementioned conventions and codes.

Dynamic phenomena, such as the swaying of the vessel due to waves, are not studied separately. These phenomena are taken into account within the criteria of the SOLAS regulations. The forming of ice on ship’s external structure is also not considered. Icing is an issue related to the intact stability and is excluded, as this thesis concentrates on the damage stability of a ship.

2 Damage stability

2.1 General

Stability is the vessel's ability to resist inclination and to return to equilibrium state. In principle, there are two conditions for a ship to be considered stable. Firstly, the forces and moments acting on the ship, made up of ship's weight, buoyancy and external loading, must be balanced. This means that the resultant force and moment have to be zero. Secondly, the ship has to return to its original state and position after the external disturbance is removed. When a ship is damaged, its stability usually decreases significantly. This must be taken into account in the design in the form of stability reserve, so that the ship survives even when damaged.

In ship design, damage stability was not taken into account before 1850s and even then, only for war ships. At first, only the ship's ability to float after damage was considered. Broader study of damage stability for passenger ships started in more rapid fashion after the sinking of *Titanic* in 1912. Damage stability means the ship's ability to keep its stability after it has been damaged. When damage stability is studied, it is assumed that the ship has suffered different sized damages at various points of the hull. The effect of the damages to the ship's equilibrium and stability is then calculated. This chapter presents factors affecting stability in general and especially damage stability.

2.2 Small angles

The stability of a vessel at small angles is called initial stability. When dealing with small angles, the vessel is assumed to have vertical sides and the waterplane area is assumed to remain constant. To illustrate the ship heeling at a small angle, figure 1 shows a ship heeling by the external moment M_{ulk}.

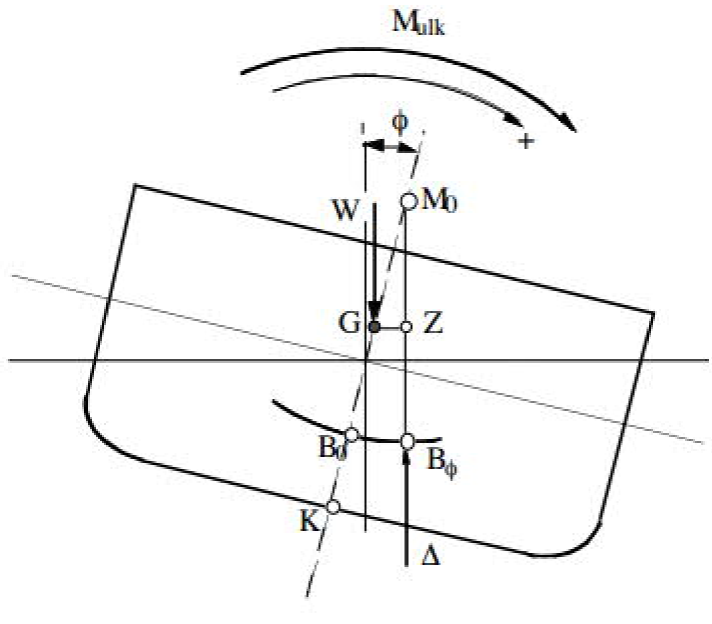


Figure 1. Initial stability model [1]

The external moment causes the ship to heel by a small angle ϕ and causes the buoyancy point B to shift from its original position B_0 along the buoyancy curve to B_ϕ. The buoyancy vector Δ is perpendicular to the waterline and intersects the symmetry plane at the metacenter M. The ship's weight W and buoyancy are equal but opposite forces and therefore the righting moment can be calculated:

$$M_{st} = -\Delta \boldsymbol{GM_0} \sin\phi \approx -\Delta \boldsymbol{GM_0} \phi \tag{1}$$

, where GM_0 is the metacentric height.

When the sum of the righting moment M_{st} and the external moment M_{ulk} is zero, the ship is statically in balance. Therefore, for the ship to be stable the metacentric height must be positive, i.e. the metacenter must be located above the center of gravity G.

The metacentric height can be expressed:

$$\boldsymbol{GM_0 = KB_0 + B_0M_0 - KG} \tag{2}$$

Where KB_0 is the z-coordinate of the buoyancy center (K is the keel point located on the centerline of the ship), KG the z-coordinate of the center of gravity and B_0M_0 is the metacentric radius, which is calculated:

$$\boldsymbol{B_0M_0} = \frac{I_T}{\nabla} \tag{3}$$

, where I_T is the moment of inertia of the waterplane area along the x-axis and ∇ is the volume of displacement.

2.3 Large angles

With heel angles exceeding 6 degrees, the initial stability model does not usually apply. The B-curve is no longer a part of the arc of a circle and the metacenter does not stay at its original position. Usually, large inclination causes the metacenter to move upwards and off the symmetry plane, as illustrated in figure 2.

The assumption made of the waterplane area of the ship remaining constant is no longer applicable in the case of large inclination angles and the midpoint of the waterplane area (the center of flotation) shifts accordingly.

When studying large inclination angles, the stability of a ship is usually described with the length of the righting arm. The righting moment can then be calculated:

$$M_{st} = GZ \cdot \Delta \tag{4}$$

, where GZ is the length of the righting arm. [1]

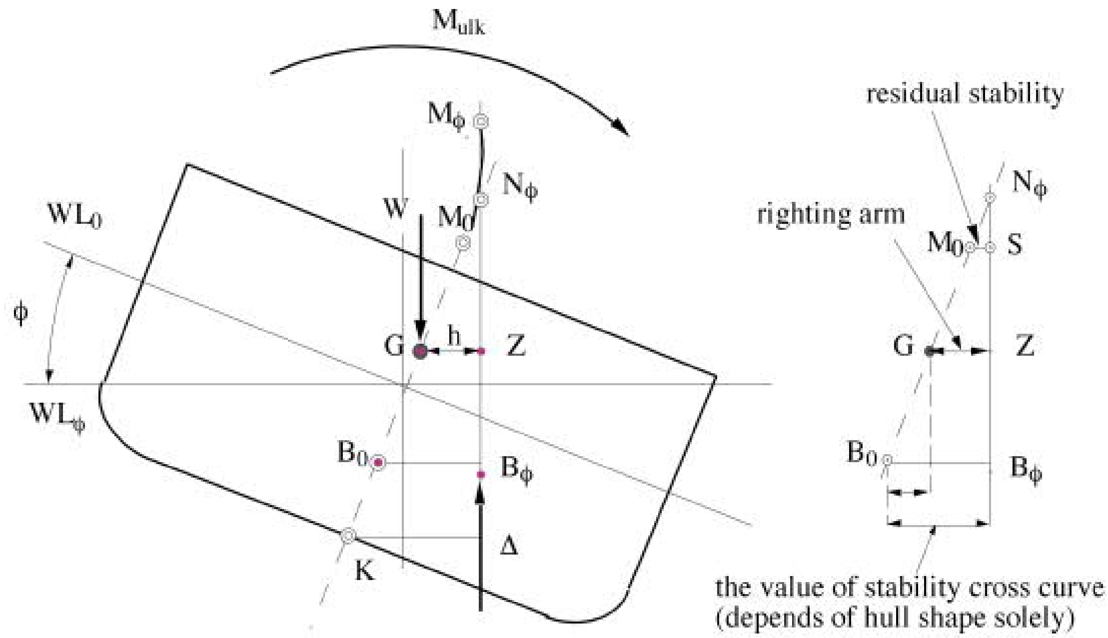


Figure 2. Stability lever at large heel angles [1]

2.4 Effect of a moving mass

Containers hoisted by a ship's own crane, poorly secured cargo, the free surfaces of transported liquid cargo etc. can cause part of the mass on board to shift and thus move the position of the center of gravity. In the case of a damaged ship, the free surface of the water flooding in the damaged compartments is also a moving mass. The center of gravity of the flood water is free to follow the ship's heeling motion and decrease the stability of the ship. The rise of the center of gravity due to free surface effect at small inclinations is:

$$GG_1 = \frac{1}{\Delta}\sum_i^n y_i i_{x_i} \tag{5}$$

, where the moments of inertia with respect to the longitudinal axis is

$$i_x = \frac{b^3 l}{12} \tag{6}$$

The breadth of the tank has a strong effect on the loss of buoyancy caused by the free surface effect. [2]

2.5 Added weight or lost buoyancy

To assess the stability of a damaged ship, there are two methods. These methods are the method of added weight and the method of lost buoyancy, which examine the damage condition from different points of view. In the method of added weight, the buoyancy of a damaged ship is the sum of the buoyancy of the ship before damage condition and the weight of the flooded water. Therefore, the buoyancy and the position of the center of gravity change.

In the method of lost buoyancy, the flooded compartments are excluded from the volume of the ship. The weight of the ship and the position of the center of gravity do not change. Which method is used depends on the category of flooded compartment in question (see figure 3). The added weight method can be used when the flooded compartment is fully filled with water and does not have a free surface (category 1) or when the water level in the flooded compartment does not extend to sea level and therefore stays flat and parallel to the sea water surface (category 2). The method of lost buoyancy is used when the water in the flooded compartment extends to the sea water level (category 3).

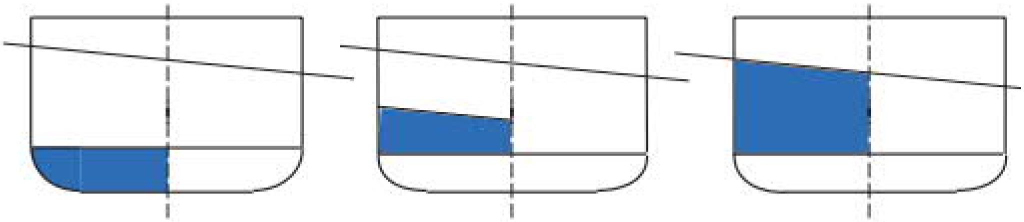


Figure 3. From left to right: category 1, 2 and 3 of flooded compartments [1]

Both methods describe the damage condition realistically and give at the final stage the same draught, angle of inclination and righting moment. However, due to the different approaches of the methods, they give different displacement, center of gravity and metacentric height. In the damage stability regulations of SOLAS, it is expected that the method of lost buoyancy is used. [1]

2.6 Effect of weather conditions

Ship can lose stability in waves in many ways. A ship travelling at forward speed encountering regular or irregular stern quartering waves with low encountering frequencies can experience static loss of stability. In this type of loss of stability, the ship experiences temporarily critically reduced righting arm, which can lead to the ship capsizing.

Dynamic loss of stability can occur when extreme rolling motions and lack of righting energy affect the ship. In the case of dynamic rolling, the ship rolls to the windward side in the wave through and to the leeward side on the wave crest, spending more time in the wave crest due to surging. Therefore, the righting arm reduces and restores asymmetrically. The roll motion can build up over a number of wave encounters to a critical level causing the ship to capsize, usually to the leeward side.

Ship in longitudinal head or following waves may experience large amplitude roll motions caused by the periodic changes in the static righting arm due to the time-varying roll restoring characteristics. This is called parametric excitation and it is characterized by roll motions occurring at around the natural roll period and twice the encounter period. Resonant excitation can happen when a ship is excited at or close to its natural roll frequency. Severe roll motion overwhelming the ship due to steep, breaking waves can cause impact excitation, which is especially dangerous for small ships in steep seas.

The wave-induced, undesired, large amplitude change in heading angle is called broaching. It can happen in three ways; by a single wave; due to successive overtaking waves at low speed; or due to low frequency, large amplitude yaw motions. [3]

In addition to waves, wind can also be problematic for the ship's stability. Difficult weather conditions may cause accidents to ships, which in turn can cause damage. Strong, gusty wind or heavy sea can induce an inclining moment. To return to an upright position, the ship must do work equal but opposite to the work created by the inclining moment. The damage stability regulations can acknowledge this by setting a minimum area that must be under the positive side of the GZ-curve and by limiting the inclination angle up to which the area is calculated.

2.7 Consequences of damage

The extent and location of the damage are key factors regarding the stability of the ship and through that, the risk of losing the ship. SOLAS (International Convention for the Safety of Life at Sea) has collected statistics on damages, which serves as a base for the damage stability regulations. In the statistics, the length of the damage varies between one and 30 meters, with the smallest damages typically not causing flooding, because they do not extend below the waterline. If there is flooding, it can have several consequences.

As the water floods in, there will be change in draught. The draught increases until the displacement equals the displacement of the ship before the damage with the flooded water in compartments subtracted. The ship will also trim until the center of gravity of the displacement of the damaged ship settles to the same vertical latitudinal level as the center of gravity of the damaged ship.

If the damage is located asymmetrically in comparison with the centerline of the ship, the ship will heel to the damaged side until the center of gravity of the displacement of the damaged ship is at the same vertical longitudinal level as the center of gravity of the damaged ship. The ship can also heel even in a symmetrical damage case, if the damage has caused the metacentric height $\boldsymbol{GM}$ to be negative. In that case, the ship heels until the $\boldsymbol{GM}$ is positive again. In both trimming and heeling, large angles may immerse openings, which will cause water to flood in through them and cause even bigger inclination.

Normally, the flooding caused by damage will affect $\boldsymbol{GM}$ negatively. The height of the center of buoyancy $\boldsymbol{KB}$ will raise due to the increase of draught and the ship trimming. The decreasing of waterplane decreases the radius of curvature $\boldsymbol{BM}$. On the other hand, the increase of draught causes $\boldsymbol{BM}$ to increase. The change in $\boldsymbol{GM}$ can be calculated:

$$\boldsymbol{GM} = \boldsymbol{KB} + \boldsymbol{BM} - \boldsymbol{KG} \qquad (7)$$

And the change in $\boldsymbol{BM}$ can be calculated:

$$\boldsymbol{BM} = \frac{I_{T1}}{\nabla_{\mathbf{1}}} - \frac{I_{T0}}{\nabla_{\mathbf{0}}} = \frac{V_W}{\nabla_{\mathbf{0}} + V_W}\left(\frac{1}{A_W}\frac{I_T}{T} - \boldsymbol{BM_0}\right) \qquad (8)$$

, where A_w is the waterplane area and V_w is the volume of the flooded water

When the relation of breadth/draught is large and the curves of the ship are V-shaped, the moment of inertia of the waterplane I_T increases, when additional water floods in. This causes an increase in the value of ***BM***, and thus also increases ***GM***.

The increase of draught causes the freeboard to decrease. This can cause the positive area under GZ-curve to decrease and make the ship more susceptible to external loads. If parts of the ship have bulkheads extending above the bulkhead deck, they can have positive effect on the righting moment. They will have an especially positive effect at the stern and bow. The displacement reserve at midship has less impact.

If achieving the equilibrium state of the ship requires the trimming, heeling and increase of draught to cause the flooding to extend outside the watertight part of the ship, the ship will not achieve equilibrium. Instead, the ship will sink and possibly before that capsize. If ***GM*** is not lost at flooding, it is possible to try limit flooding and pump out the flooded water and thus save the ship. [1]

3 Current regulation

3.1 IMO

Because of the international nature of the shipping industry, it has been known for a long time that regulations for it should be coordinated on an international level. Hence, the United Nations Maritime Conference convened in Geneva from 19 February to 6 March 1948 and established the Intergovernmental Maritime Consultative Organization (IMCO) with an international treaty. The treaty entered into force on 17 March 1958. IMCO had its first meeting in 1959. The name of IMCO was changed to the International Maritime Organization (IMO) in resolutions A.358(IX) of 14 November 1975 and A.371(X) of 9 November 1977. [4]

IMO has 172 member states, 171 of which are UN member states, and three associate members. Its headquarter is located in London, United Kingdom. IMO is a specialized agency of United Nations, which sets standards globally for the safety, security and environmental performance of international shipping. The main purpose of IMO is to regulate the shipping industry in such a manner that ship operators cannot seek advantage over each other by disregarding safety of human life, cargo and environment.

International shipping covers more than 80 per cent of global trade and needs regulations and standards agreed, adopted and enforced internationally. This is provided by the regulatory framework of IMO. IMO regulated areas include ship design, construction, manning, operation, equipment and disposal to cover all aspects of international shipping. IMO slogan [5] sums up the principles and goals of the organization: “safe, secure and efficient shipping on clean oceans”.

IMO comprises of an assembly, a council, five main committees and several sub-committees supporting the work of the main committees. The assembly, open for participation for all the member states, is the governing body of IMO and it meets every two years. The council, comprised of 40 member states elected by the assembly, acts as the governing body between the assembly sessions. The committees conduct the technical work of IMO. The five main committees are the Maritime Safety Committee, the Marine Environment Protection Committee, the Legal Committee, the Facilitation Committee and the Technical Co-operation Committee. IMO is supported by a permanent secretariat of people representing the member states of the organization and headed by a periodically elected Secretary-General.

IMO has some 60 legal instruments as guidance to the regulatory development of its member states to improve safety at sea, help trading between seafaring states and protect the marine environment. Among the legal instruments of IMO are a number of conventions, codes and regulations such as MARPOL Convention governing the pollution from ships, SOLAS for the safety regulation and COLREG for the navigation rules, to mention but a few. Other conventions, codes and regulation set rules and standards for training of the crew, oil pollution, ballast water treatment, communication between vessels etc. In this thesis, the damage stability regulations of SOLAS are studied and used in the design and evaluation of the case ship. [5]

3.2 SOLAS

3.2.1 History

The International Convention for the Safety of Life at Sea (SOLAS) is one of the oldest conventions regarding the safety of maritime traffic. It is an international maritime treaty, which determines minimum safety standards in the construction, equipment and operation of merchant ships. SOLAS is generally regarded as the most important international treaty for the safety of merchant ships. SOLAS requires that its signatory flag states ensure that ships under their flag comply at least with the standards set in SOLAS. Approximately 99.14% of the merchant ships of the world in terms of gross tonnage are flagged by the 163 contracting states of SOLAS. [6]

The first SOLAS conference convened in 1914. In the early 20th century, passenger ships were much more common than they are nowadays, because there was no air traffic and great number of people were emigrating mainly from Europe to the Americas. Hundreds of people were perished annually in accidents on the sea. However, it was not until *Titanic* sank in April 1912 causing the death of 1500 passengers and crew members, that United Kingdom Government proposed holding a conference to develop international regulations for the safety standards of ships. The conference was attended by 13 countries and was mainly concerned with the safety of human life. The conference produced the first SOLAS convention, which was adopted on 20 January 1914 to be entered into force in July 1915. However, the start of World War I prevented the convention's entry to force, although many nations adopted many of its provisions independently.

The first SOLAS convention introduced new international requirements for the safety of navigation, life-saving appliances, watertight and fire-resistant bulkheads, radiotelegraph equipment and fire prevention and firefighting appliances on passenger ships. Also, the conference agreed on establishing the North Atlantic ice patrol.

In 1929, the second SOLAS convention was held in London with representatives from 18 countries attending. The convention, which entered into force in 1933, included several new regulations and revised the international regulations for preventing collisions.

The third SOLAS convention in 1948 was held for the regulations to catch up with the technical developments of the past years and was attended by 34 countries. While following the same patterns as the previous conventions, the third SOLAS convention had more detailed regulations and covered wider range of ships. Updates were made, for example, to watertight subdivision of passenger ships, stability standards, structural fire protection and radio communications. Also, new chapter dealing with carriage of dangerous cargo was included.

In 1948, the year of the third SOLAS convention, UN established IMO and there was finally a permanent international body capable of adopting regulations and legislation concerning all aspects of international shipping, including those covered in SOLAS. In 1960, IMO held the fourth SOLAS convention, which had representatives of 55 countries attending, a significant increase from the previous convention twelve years earlier. The convention again addressed the many technical improvements of the field of shipping industry. In the convention a procedure for adopting amendments was introduced, which stated that amendments could enter into force twelve months after being accepted by two-thirds of contracting parties of the parent convention. However, the growing number of member states of such international organizations as IMO meant that for the amendments to come into force would take so long, that the they would be out of date before the date of their entry to force.

3.2.2 SOLAS 1974

To speed up the process of bringing amendments into force, IMO decided that there was a need for a new SOLAS convention. It was determined that the new convention should include all the amendments made thus far and introduce a new procedure which would ensure that future amendments would enter into force within a reasonably short period of time.

In 1974, the fifth SOLAS convention was held in London with 71 countries attending. It introduced a new tacit amendment procedure. The new procedure ensured a faster pace of bringing amendments into force by assuming that the contracting governments accept the amendments unless they make their objection known within a specified time.

The tacit amendment procedure is included in Article VIII of the SOLAS convention. It stipulates that amendments to all chapters excluding Chapter I will be considered accepted within two years or a specified time period fixed at the time of adoption unless they are rejected by sufficient number of contracting governments within set time period. Sufficient number of contracting governments is either one third of them or any number of contracting governments whose combined merchant fleets represent at least 50 per cent of world gross tonnage.

SOLAS 1974 entered into force in 1980 and with amendments it is the convention currently in force. It is unlikely that it will be replaced as the tacit amendment procedure enables IMO to react to technical developments and recognize flaws in a rapid manner.

The 1974 SOLAS convention included the chapters I-VIII, which had been established in the first SOLAS convention. Nowadays, the convention also has chapters IX-XIV, which have been added as amendments. The convention on the International Regulations for Preventing Collision at Sea was adopted in an IMO conference in 1972, so SOLAS 1974 was the first conference where Collision Regulations were not revised as it was decided, that they should no longer to be appended to the SOLAS convention.

3.2.3 SOLAS 1990

Several amendments were made to different parts of the 1974 SOLAS convention over the years. For this thesis, the amendments made in May 1990 are of particular interest. These amendments added a new part B-1 of Chapter II-1, which introduced a new way to determine the damage stability and subdivision. The requirements only applied to cargo ships 100 meters or more of length, not to passenger ships, but they are of interest for this thesis, because the requirements were based on “probabilistic” concept of survival. The probabilistic concept was developed by studying IMO’s collected data relating to collisions. A pattern of accidents could be detected and the findings could be utilized in practical improvement of ship design. The probabilistic method gives more realistic results than the deterministic method used before, because the former is based on statistical evidence whereas the principles of the latter are theoretical in concept. [7]

For cargo ships, required subdivision index R was determined based on the statistics collected from collisions and calculation for the attained A index based on probabilities was also determined. It was stated that A must be greater or equal to R. For passenger ships, deterministic method was still used. [8]

3.2.4 SOLAS 2009

The probabilistic method was introduced as an alternative for calculating damage stability of passenger ships already in 1973 [7]. However, it was not until SOLAS 2009 that the probabilistic method was taken into use as a primary calculation method for passenger ships while unifying the calculation methods for cargo and passenger ships. When moving from the deterministic method to the probabilistic method, it was important to keep the safety level at the same level.

In the probabilistic method, R-index and A-index are calculated and for the ship to be stable and sufficiently safe, it must be ascertained that $A \geq R$. The probabilistic method takes into account all possible damage combinations of length, height and penetration depth and survivability is calculated based on statistical data from damages to other ships. Because the probabilistic method considers all the damage cases, the calculation process takes longer than with the deterministic method, where the amount of damage cases is limited. The probabilistic method is the more extensive of the two methods and it allows novel designs to achieve the same level of safety as conventional design, which is not possible with the deterministic method.

In SOLAS 2009 the attained subdivision index A is calculated as the weighted sum of the partial indices A_s, A_p and A_l calculated for the draughts d_s (deepest subdivision draught), d_p (partial subdivision draught) and d_l (lightest service draught):

$$A = 0.4A_s + 0.4A_p + 0.2A_l \qquad (9)$$

$$A = \sum p_i s_i \qquad (10)$$

, where p_i is the probability of all damage cases, i.e. the probability that compartment (or group of compartments) i may be flooded excluding the effect of horizontal subdivision

, and s_i is the probability of surviving of those damage cases, i.e. the probability of survival after the compartment (or group of compartments) i is flooded including the effect of horizontal subdivision.

In the case of passenger ships, SOLAS 2009 determines the required subdivision index R to be:

$$R = 1 - \frac{5000}{L_s + 2.5N + 15225} \qquad (11)$$

, where $N = N_1 + 2N_2$ (12)

N_1 = number of persons for whom lifeboats are provided

N_2 = number of persons the ship is permitted to carry in excess of N_1

As this thesis is written, the damage stability regulations of SOLAS 2009 are in force [9]. The probabilistic method adopted for cruise ships in SOLAS 2009 is an important improvement for approaching the damage stability of a ship. In situations described by deterministic regulations the ship either passes or fails, there is no middle ground. When using a probabilistic approach, non-survival case can be acceptable for some cases, as long as the likelihood for the particular case to happen is low enough. This does not jeopardize the safety of the ship, because achieving the required safety level is still mandatory. Therefore, the probabilistic method ensures the same safety level as the deterministic method while also removing from consideration the cases, which are very unlikely to happen. Thus, more realistic representation of the safety level of a ship in damaged situations is achieved. The results given by the probabilistic method are more realistic also because they are based on statistical data of real cases. [10]

However, while the adoption of the probabilistic approach is an improvement for the damage stability calculation, the formulation for the s-factor used in the probabilistic method in SOLAS is not optimal for cruise ships. To achieve a harmonized solution, the general formulation of the s-factor for cargo ships is used for passenger ships. This is irrational, because cruise ships are considerably different from both cargo ships and RoPax vessels, on which the calculation is based on. [11].

From a cruise ship designer's point of view, the damage stability regulations of SOLAS 2009 have both benefits and downsides. On the one hand, the probabilistic method allows more freedom regarding for example the placement of watertight bulkheads. This is due to the elimination of the limiting pass/fail criteria of the deterministic method. This means that any such subdivision is acceptable, which provides that if the survivability of the damage is not 100%, the probability of the damage to happen is very low. On the other hand, SOLAS 2009 underestimates the survivability of cruise ships. The formulation of the s-factor does not properly rate possible solutions for improving the cruise ship survivability. This hinders the design work, as the designers' knowledge of improving the survivability does not match with the results given by calculations based on SOLAS 2009 regulations. [10] & [12]

There are some simplifications in SOLAS. The simplifications limit the ability of SOLAS to represent real-life situations. Firstly, the attained index A does not include grounding, only collision. Damages caused by grounding are different to damages caused by collision, because in grounding the location of damages is different, typically more in the bottom than on the sides. Also, in grounding the effect of stranding is significant to the stability of the ship. [13] & [14]

Secondly, while the moment caused by wind is accounted for, the forces and moments caused by waves are ignored. The probability of sea state is not considered, even though in reality the waves can have a huge effect on the ship by heeling it over the angle that it would reach just because of the damage suffered. [9]

Lastly, the s-factor does not cover complex subdivision. As has been discussed earlier in this thesis, the accuracy of the s-factor for cruise ships is questionable. However, for simple subdivisions it can be calculated logically. For more innovative and complex subdivisions, the calculation does not apply. This is not necessarily a major issue, because simple solutions in subdivision are preferable, as they are easier to put into practice in construction. [13]

3.3 Polar Code

3.3.1 General

The International Code for Ships Operating in Polar Waters, better known as Polar Code, is a set of regulations concerning shipping in Polar regions. It was adopted by IMO in 2014 and entered into force on 1 January 2017, based on voluntary guidelines from 2002 and 2010. Polar Code protects the two polar regions Arctic and Antarctic (figures 4 and 5) from maritime risks. The regulations set out in the Polar Code relate principally to ice navigation and ship design for polar areas. [15]

Polar Code defines three categories for ships, based on their ice classes, not on their ice breaking capabilities. The categories are as presented in the Polar Code [16]:

- Category A ship means a ship designed for operation in polar waters in at least medium first-year ice, which may include old ice inclusions.

- Category B ship means a ship not included in category A, designed for operation in polar waters in at least thin first-year ice, which may include old ice inclusions.

- Category C ship means a ship designed to operate in open water or in ice conditions less severe than those included in categories A and B.

Figure 4. Maximum extent of Arctic area (northern hemisphere) [16]

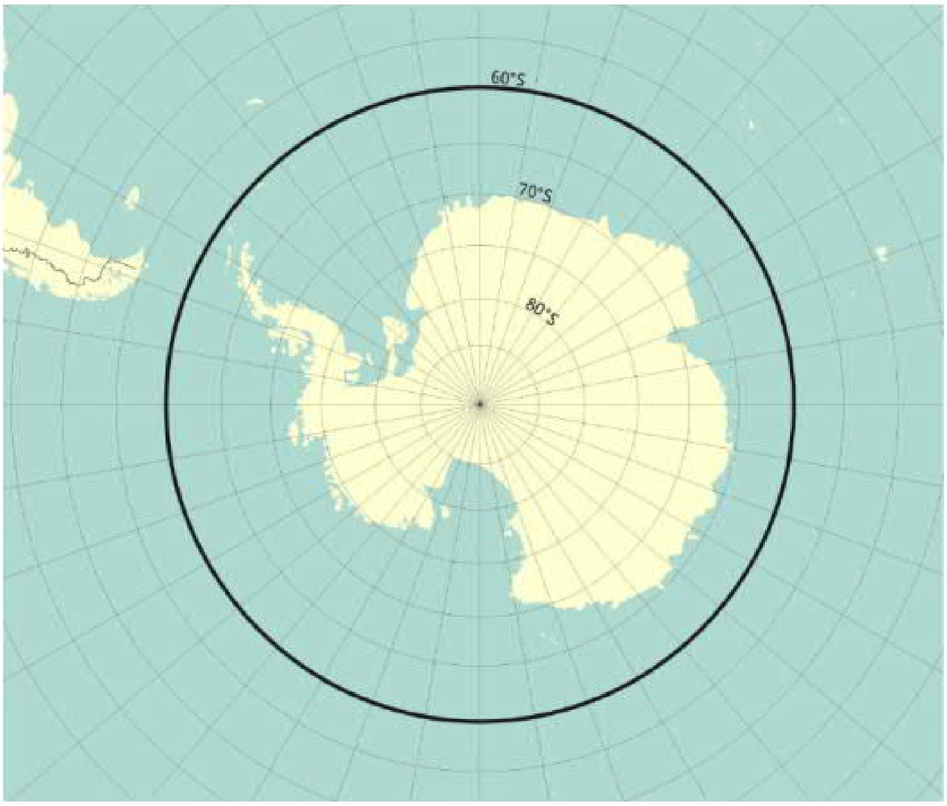


Figure 5. Maximum extent of Antarctic area (southern hemisphere) [16]

By most parts, the Polar Code mandatory rules apply to both new ships and all existing ships, including those already in operation and those which will be converted for polar waters. However, there are 10 requirements that only apply to new-builds. Damage stability regulation 4.3.2, which will be covered in chapter 3.3.2 of this thesis, is one of the requirements only applicable to new-builds. [16]

Due to the increasing amount of marine traffic, Polar Code is a needed addition to the regulatory framework of the seas. The regulations of SOLAS are designed to apply for ships operating in open waters. The Arctic and Antarctic waters are very different environments from open sea because of their extreme weather and ice conditions. Therefore, the conditions on which SOLAS regulations are based, do not realistically represent the polar conditions.

A major issue with Polar Code is how much it references SOLAS. As mentioned before, the open water conditions considered in SOLAS do not apply to polar waters. Therefore, using SOLAS definitions and limitations as a basis for Polar Code can cause problems. For example, SOLAS as the main rule defines that it applies only to ships on international voyages. Therefore, Polar Code also applies only to ships operating between different countries. This definition would exclude ships operating exclusively off Antarctica. This should not be the case, as ships operating off Antarctica face same perils as other ships operating in polar waters, regardless of which port they originate from. Non-international voyages should also be required to comply with Polar Code in order to get the full benefit of the regime. [9] & [17]

SOLAS [9] also states that "ships constructed before 1 January 2017 shall meet the relevant requirements of the Polar Code by the first intermediate or renewal survey, whichever occurs first, after 1 January 2018". Although it is defined in Polar Code, which requirements are for all ships and which just for new-builds, the term "relevant requirements" is quite vague. Also, military vessels are exempt from the Polar Code regulations according to SOLAS. It would be beneficial to consider specifically for polar operations whether new-builds, military vessels and non-internationally operating ships have to comply with Polar Code, rather than relying solely on the application of SOLAS rules. [17]

3.3.2 Damage stability regulations

Damage stability regulations in Polar Code consist of a supplement to the calculation of s_i in SOLAS II-1 part B1 and deterministic calculation of the ice damage extent. Regulation 4.3.2 in Polar Code states that following ice damage $s_i = 1$ for all loading conditions used to calculate attained subdivision index A. In SOLAS 2009 the calculation for s_i is as follows [9]:

$$s_{final,i} = K \cdot [\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16}]^{\frac{1}{4}} \tag{13}$$

, where as defined [9]:

GZ_{max} is not to be taken as more than 0.12 m;

Range is not to be taken as more than 16°;

$K = 1 \quad if\ \theta_e \leq \theta min$

$K = 0 \quad if\ \theta_e \geq \theta max$

$K = \sqrt{\frac{\theta\ max - \theta e}{\theta\ max - \theta\ min}}$ *otherwise,*

where:

θ_{min} is 7° for passenger ships and 25° for cargo ships; and

θ_{max} is 15° for passenger ships and 30° for cargo ships.

In SOLAS 2020 the calculation of s_i is expressed slightly differently, but it is essentially the same for cruise ships (for RoPax there is a difference in calculation between SOLAS 2009 and 2020) [18]:

$$s_{final,i} = K \cdot [\frac{GZ_{max}}{TGZ_{max}} \cdot \frac{Range}{TRange}]^{\frac{1}{4}} \tag{14}$$

, where the definition from SOLAS 2009 differs in following ways [18]:

GZmax is not to be taken as more than TGZmax;

Range is not to be taken as more than TRange;

TGZmax = 0.20 m, for ro-ro passenger ships each damage case that involves a ro-ro space,

TGZmax = 0.12 m, otherwise;

TRange = 20º, for ro-ro passenger ships each damage case that involves a ro-ro space,

TRange = 16º, otherwise;

The longitudinal and vertical ice damage extents in the damage stability regulation of Polar Code are dependent on the size of the ship with these damage extents defined as percentages of the dimensions of the ship. The larger the ship is, the bigger the damage length and height are. The transverse penetration extent is always 760 mm regardless of the size of the ship. In Polar Code, the damage dimensions and locations are expressed [16]:

.1 the longitudinal extent is 4.5% of the upper ice waterline length if centred forward of the maximum breadth on the upper ice waterline, and 1.5% of upper ice waterline length otherwise, and shall be assumed at any longitudinal position along the ship's length;

.2 the transverse penetration extent is 760 mm, measured normal to the shell over the full extent of the damage; and

.3 the vertical extent is the lesser of 20% of the upper ice waterline draught or the longitudinal extent, and shall be assumed at any vertical position between the keel and 120% of the upper ice waterline draught.

The damage stability regulations of Polar Code, which are discussed in its fourth chapter, are applicable to ships of categories A and B [16]. Many of the passenger ships designed for polar waters, usually for polar cruise -experiences, will probably be designed in category C [19]. The damage stability regulation is not mandatory for these ships, but for the safety of the polar marine traffic, it would be wise to consider Polar Code rules for category C ships also, when possible.

3.3.3 Interpretation of damage stability regulations

The damage stability rules in Polar Code are expressed in a concise manner, but they leave room for some interpretation. Firstly, it is not clear, whether the longitudinal extent at the areas where the hull has curvature (namely stern and bow) is measured parallel to X-axis (figure 6) or following the curvature of the outer surface of the shell (figure 7). The former interpretation is backed by section 1 of rule 4.3.2.2, where waterline length is mentioned. Because waterline length is measured from the XZ-projection, it could be assumed that same measurement method applies to measuring the damage length. The latter interpretation is supported by section 2 of the rule, where it is said that transverse penetration is measured to the normal direction of the hull. Therefore, it could be assumed that the damage length should take into account the possible curvature of the hull.

Third interpretation could be that the extent would be measured from the curve defined by the 760 mm transverse penetration extent, parallel to X-axis (figure 8), which would give the largest “damage-box”. However, there perhaps is not an argument compelling enough for explaining why the longitudinal extent of the damage would not be measured from the full breadth of the upper ice water line. Therefore, the interpretations shown in figures 6 and 7 are considered as the sensible options for interpretation.

Coordinate system used here is right-handed with the positive direction of the Z-axis being from the keel line to the direction of the main deck.

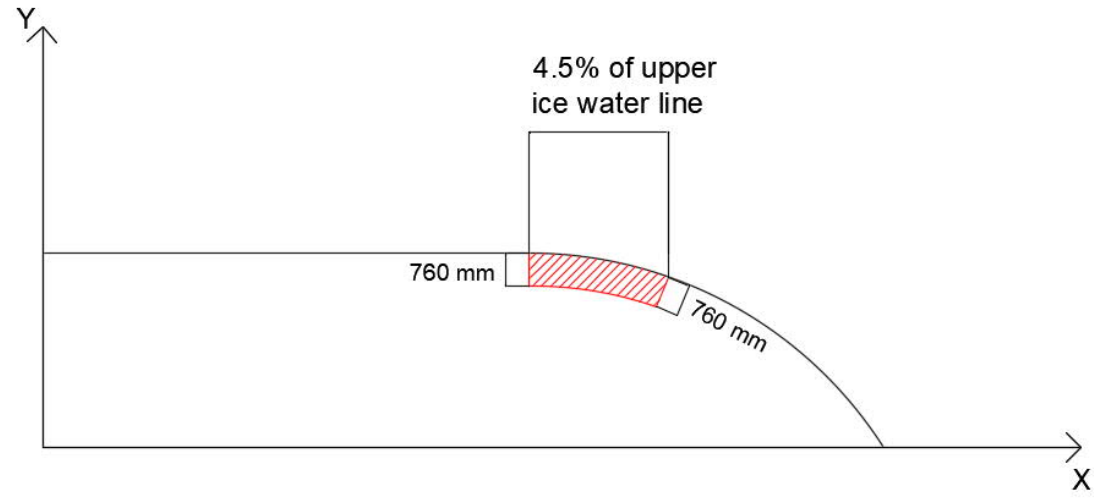


Figure 6. Damage length measured parallel to X-axis

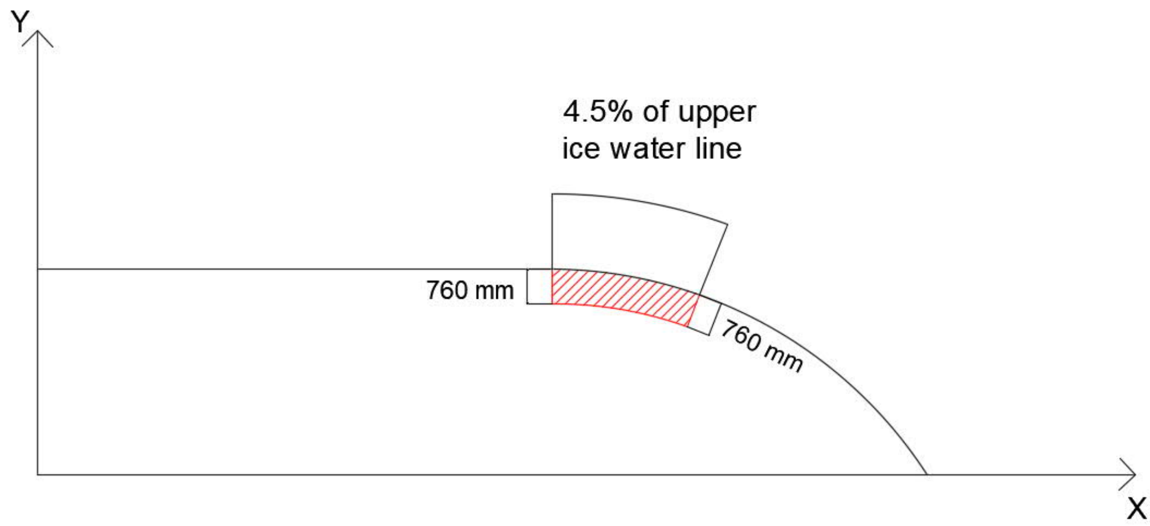


Figure 7. Damage length measured from the outer surface of the shell, following the curvature of the shell

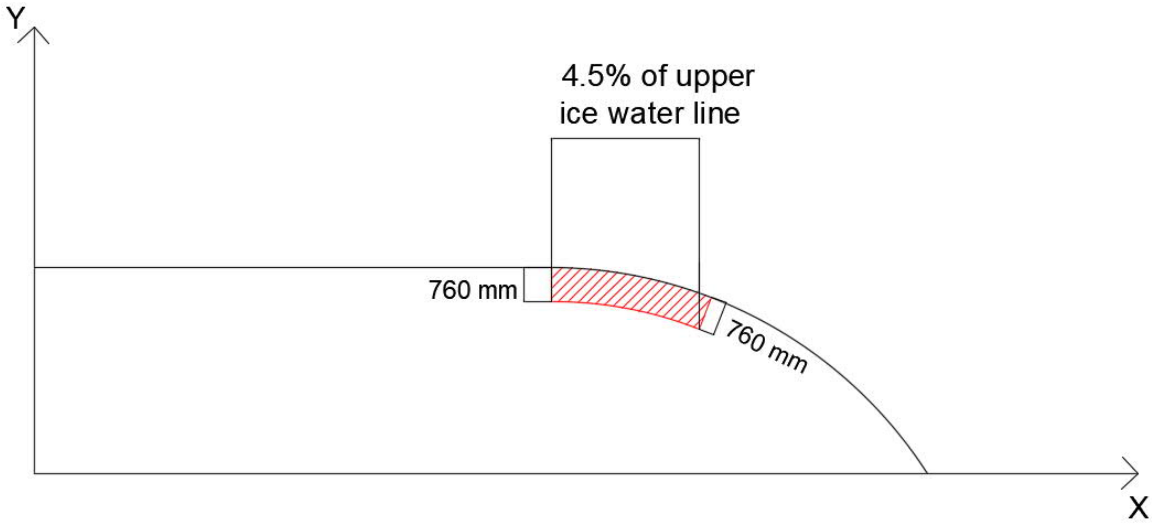


Figure 8. Damage length measured parallel to X-axis from the inner part of the damage-box (760 mm inside the hull)

Currently, there is no definitive interpretation on how to measure the damage length. In this thesis, the interpretation illustrated in figure 6 is chosen, because it gives larger volume to the damage-box. This means, that the values achieved in damage stability calculation are more conservative and therefore give higher level of safety. Correspondingly, the vertical extent of the damage is measured parallel to Z-axis.

The second issue regarding the interpretation of the damage stability rules is that it is not stated in which direction vertical extent is measured in the bottom area of the hull. Ihalainen [19] and Huuskonen [20] have interpreted in their Master's Theses that the vertical extent should be measured in Y-direction, because in the bottom area of the hull the damage penetration is measured in Z-direction. The same interpretation is used here since all ships also have a double bottom, which has the height of at least 760 mm and therefore larger than the transversal extent of the damage [9] & [18].

Polar Code also has an overarching issue regarding the interpretation. In the development of Polar Code, goal-oriented standards were recommended instead of prescriptive and deterministic regulations. The goal-based approach is apparent in the damage stability chapter, since all the chapters in the safety part start with a description of overall goals and functional requirements. However, the prescriptive regulations supporting the goals and functional requirements are highly technical and precise. This leads to a mixture of vague and precise provisions, which gives an inconsistent image on how the regulations should be interpreted. The goal-based approach in developing Polar Code is not apparent, since most of the regulations are inflexible and not discretionary. [17] & [21]

In addition of being occasionally vague, Polar Code is missing some important parts, such as testing standards. The missing of these does not affect the damage stability directly but has a negative effect on the credibility of the regulations and is a clear indicator, that Polar Code is not yet ready, and will need further amendments to fulfil its potential as a regulator for polar operations. [17]

4 Improving damage stability

4.1 Background

Rule changes often take place after major accidents. Accidents bring attention to problems, which gives momentum to find solutions to these problems. Accidents also give realistic information on what needs to be changed and bring to light problems that were previously unknown. Two accident cases are introduced here to show why regulations to improve damage stability are needed. The first case concerns mainly Polar Code while the second case involves issues related to SOLAS.

4.1.1 MV Explorer, 2007

On 23 November 2007, a Liberian-register cruise ship *Explorer* sank in the Antarctic waters after colliding with a section of land ice near King George Island in the Southern Ocean. *Explorer* was built in 1969 to 1A1 ICE-A class and remained in its old class notation all through its service, even though higher standards for ships traveling in icy waters had already been introduced. The ship had completed more than 250 journeys to the Antarctic waters, so both the ice class and the capabilities of *Explorer* seemed to be suitable for polar operations.

Nevertheless, the ship was not capable to handle impact with the hard land ice amongst the first-year ice. Also, a watertight door between compartments was open, allowing the flooding to extend to two compartments. The rules of the time obligated the ship to be able to survive only one-compartment damages.

Even if the design and the construction are done to the best current knowledge, the changes in operational areas and purposes may mean that the ship may not be able to safely fulfil its purpose. Polar Code was designed to regulate ships operating in polar waters, but it is important to remember that it will not be until some time passes that we will see whether Polar Code works in reality. [22]

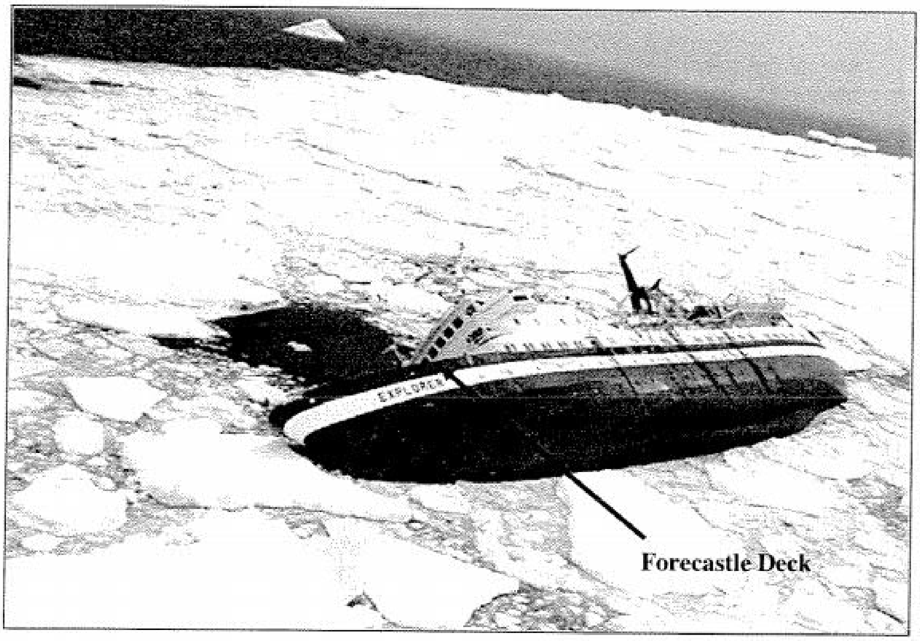


Figure 9. Sinking of *Explorer* [22]

4.1.2 Costa Concordia, 2012

On 13 January 2012, an Italian cruise ship *Costa Concordia* capsized and sank near Tuscany after an impact with an underwater rock. The ship had been operating since 2005 and was built to comply with the SOLAS regulations in force at the time.

The initial collision was due to errors made by the captain and crew (deviating from the course, too high speed in night conditions etc.). The immediate and irreversible flooding, however, was due to poor level of damage stability. *Costa Concordia*, while built to the standards of its time, was not able to withstand the flooding of two contiguous compartments. When two compartments were flooded, the ship had already met its limit conditions in terms of buoyancy, trim and heel. The flooding of three more compartments increased the draught of the ship enough to submerge the bulkhead deck and spur on the sinking. [23]

Both of the accidents mentioned here (*Costa Concordia* and *Explorer*) brought to light some lacking in regulation and were instrumental in speeding up rule changes. However, both accidents were also partly due to human errors. In the case of *Costa Concordia*, the captain chose to steer the ship into too shallow waters. The captain of the *Explorer,* who had not previously served in that position, misread the ice conditions. No amount of regulation will eliminate human error, but it can eliminate design and construction errors and therefore improve the safety significantly. [22] & [23]

Figure 10. Sinking of *Costa Concordia* [23]

4.2 Proposed alternatives for the R-index

In the 84th meeting of the MSC in 2008 concerns were raised that SOLAS 2009 did not meet the standards of SOLAS 1990. Several research projects were conducted to find if the damage stability regulations were sufficient. The result was, that based on SOLAS 2009 it would be possible to design a ship, which does not survive certain damage cases and may capsize and sink even in calm water. Different research projects suggested different calculation methods for the R-index to raise the safety level of the ships.

European Maritime Safety Agency (EMSA) had a couple of different research projects. The proposal for the R-index that EMSA 2 came up with was:

$$R \geq 0.875 \; when \; N < 100$$

$$R \geq 1 - \frac{1}{0.0845 \cdot N * 36.67 \cdot 10^{-6} \cdot N^2} \; when \; 100 \leq N \leq 375$$

$$R \geq 1 - \frac{1}{0.0845 \cdot N \cdot e^{-\left(\frac{N-250}{704}\right)}} \; when \; 375 \leq N \leq 704$$

$$R \geq 0.968 \; when \; N > 704 \tag{15}$$

In the EMSA 3 report the calculation for the R-index was the same for any number of people on board:

$$R = 1 - \frac{C1 \cdot 6200}{4 \cdot N + 20000}$$

$$where \; C1 = 0.8 - \frac{0.25}{10000} \cdot (10000 - N) \tag{16}$$

The Goal-based Damage Stability - research project (GOALDS) had two suggestions for the calculation of the R-index. In the first one the R-index is calculated differently depending on the number of people on board:

$$R = 0.9 \; when \; N < 1000$$

$$R = 0.9 + \frac{0.07}{5000} \cdot (N - 1000) \; when \; 1000 \leq N < 6000$$

$$R = 0.97 \; when \; N \geq 6000 \tag{17}$$

The second suggestion did not differentiate between different number of people on board:

$$R = 1 - \frac{2300}{5 \cdot N + 20000} \tag{18}$$

The United States of America had the following proposal for the calculation of the R-index:

$$R = 0.75 \; when \; N \leq 400$$

$$R = 1 - \frac{355.5}{N + 1022} \; when \; 400 < N \leq 1200$$

$$R = 1 - \frac{1410}{N + 7610} \; when \; N > 1200 \tag{19}$$

The proposal for the R-index from Japan was:

$$R = 0.0719 \cdot \ln(N) + 0.291 \tag{20}$$

Other research projects were also conducted. For example, BMVI studied together with German shipyards the effect of increasing the R-index for small passenger ships, special vessels and big yachts, but they were not able to find a cost-effective solution. Between 2005-2009 the EU-funded R&D project SAFEDOR concluded through series of formal safety assessments (FSA studies) that the risk to human-life could be reduced cost-effectively by raising the R-index. [24]

In 2016 a working group formed at the third meeting of IMO sub-committee on ship design and construction (SDC) was tasked with finding a functional solution for calculating the R-index. The working group studied all the proposals presented in this chapter and formed a compromise solution. Their proposal for the R-index settled halfway between the R-indices of SOLAS 2009 and GOALDS and approached the higher of the two R-indices proposed by EMSA. Their proposal for the R-index is shown in table 1. This proposal was approved at the 96th meeting of the Maritime Safety Committee (MSC). [25]

Table 1. SDC3 decision for R-index [18]

Persons on board	R
$N \leq 1000$	$R = 0.0000088 \cdot N$
$1000 < N \leq 6000$	$R = 0.0369 \cdot \ln(N + 89.048) + 0.579$
$N > 6000$ and $C1 = 0.8 - \frac{0,25}{10000} \cdot (10000 - N)$	$R = 1 - \frac{C1 \cdot 6200}{4 \cdot N + 20000}$

4.3 SOLAS 2020

At the 98th meeting of the MSC on 15 June 2017 a new proposal for the R-index by China, Japan, the Philippines and the USA was introduced. The proposal was approved unanimously and the amendments for SOLAS II-1 within resolution MSC.421(98) will come into effect for ships for which the building contract is placed on or after 1 January 2020. The new amended version of SOLAS will be known as SOLAS 2020. The approved R-index is shown in table 2.

Table 2. R-index in SOLAS 2020 [18]

Persons on board	R
$N < 400$	$R = 0.722$
$400 \leq N \leq 1350$	$R = \frac{N}{7580} + 0.66923$
$1350 < N \leq 6000$	$R = 0.0369 \cdot \ln(N + 89.048) + 0.579$
$N > 6000$	$R = 1 - \frac{852.5 + 0.03875 \cdot N}{N + 5000}$

In ships, where there are between 1350 and 6000 persons on board, the calculation method for the R-index approved at MSC 98 is the same as that suggested at SDC3 and approved at MSC 96. The calculation for the cases where the number of people on board is more than 6000 is similar to the SDC3 proposal, but with a simplified form where C1-variable is not calculated separately. In the cases, where there are less than 400 persons on board, the R-index is a constant and then up to 1350 persons on board the R-index rises as a linear function of N to meet the R-index of SDC3 proposal. The attained index A is calculated at the same way as in SOLAS 2009 (see chapter 3.2.4). The main differences to SOLAS 2009 are:

- R-index is not dependable on length
- Number of people on board is no longer divided to those who are provided with a lifeboat and to those that the ship is allowed to carry in excess, but is taken as one number
- R is constant for passenger ships with less than 400 people [18]

Despite all the research that went into finding a new R-index, the R-index approved by MSC 98 is partly political rather than technical. There is little to no technical justification to why R is constant for ships with $N < 400$. The biggest changes in the R-index from SOLAS 2009 to SOLAS 2020 happen for ships with $N < 400$ and ships with $700 < N < 2000$. [26]

SOLAS 2020 damage stability regulations improve upon the safety level set in SOLAS 2009 but do not address the simplifications or the issue regarding the s-factor, which were discussed in chapter 3.2.4 of this thesis. The general formulation of the s-factor still remains the same for RoPax and cruise ships, even though in real case experiences, the safety level has been observed to be higher than SOLAS suggests. For example, *Costa Concordia* stayed afloat for several hours, even though it was built to fulfil SOLAS 1990 standards. [23] & [13]

Numerical simulations have also shown that the survivability of cruise ships has been underestimated in SOLAS. It was found that when using a new Survivability Performance Index (SPI), which represents ship's behavior during flooding better, the differences in the s-factor to SOLAS were around 2% for RoPax and over 7% for cruise ships. [27]

The reason why the calculation of the s-factor favors RoPax vessels is that in the last 20 years, the research concerning damage stability has focused on RoPax. GOALDS [28] and EMSA [29] projects attempted to reformulate the s-factor for passenger ship, but ultimately no significant change took place. In SOLAS 2020, the only difference between RoPax and cruise in the calculation of the s-factor is, that the range of positive righting levers (GZ) and the maximum GZ have different values. The formula is the same for both types of passenger ship. The issue stems from the research project HARDER, upon which results IMO based the s-factor formulation in SOLAS 2009. HARDER had a small and homogenous sample of ships, which led to a formulation that underestimates the survivability of cruise ships. [18] & [30]

The current damage stability regulations are largely based on model tests with RoPax. This is due to the fact that model tests for cruise ships are complicated and expensive. However, there is a big difference between RoPax and cruise ships. They have different risks and accident frequencies. Also, due to different internal subdivisions they have different sinking behavior; cruise ships capsize rapidly whereas RoPax typically sink slowly. Therefore, results achieved for RoPax cannot be directly applied to cruise ships. Yet the same s-factor formulation and same level of R-index is defined for both types of ship. [30]

4.4 Combining SOLAS and Polar Code regulations

An easy solution for raising the A-index to meet the required subdivision index R of SOLAS 2020 would be increasing subdivision. The number of compartments would increase while the size of the compartments would decrease. However, because the increase of R-index from SOLAS 2009 to SOLAS 2020 can be several per cents for small ships, the required frequency of bulkheads may lead to impractical designs.

The decrease in the size of the compartments brings about a problem with Polar Code. According to Polar Code, the longitudinal extent of damage caused by ice is 4.5% of the upper ice waterline length if the center of the damage is forward of the maximum breadth of the upper ice waterline (and 1.5% in other cases). If the subdivision is very dense, meaning that there are many compartments in a short space, the ice damage will affect several compartments at once. The same problem arises when considering the transverse extent of the damage. The transverse extent of the penetration caused by ice damage is 760 mm. So, if the transverse length of the compartments near the sides of the ship is less than 760 mm, the damage will reach multiple compartments.

If a single damage involves multiple compartments, stability is considerably worse than when only one compartment is damaged. If only one watertight compartment is damaged, the damage will be limited within the watertight bulkheads. Separate damages in different parts of the ship are naturally problematic, but usually containable. If the distance between two adjacent transverse watertight bulkheads is smaller than the assumed damage length (i.e. damage extends to more than one compartment), only one of the bulkheads is considered effective according to SOLAS.

Because the longitudinal extent of damage is calculated as percentage of the upper ice waterline length, it is dependent on the dimensions of the ship. The relative effect of ice damage is therefore same for ships of all sizes, i.e. for bigger ships the longitudinal damage is assumed to be bigger than for smaller ships.

The transverse extent of penetration will affect especially smaller vessels. The transverse extent is the same for ships of all sizes, which means that for smaller ships the transverse extent of the penetration is a bigger percentage of the breadth of the ship than for larger ships. However, with the transversal extent being just 760 mm, it is highly improbable that extent of the damage would be bigger than breadth of a compartment.

SOLAS 2020 uses probabilistic method for calculating damage stability, whereas Polar Code has deterministic approach to damage stability calculation. While this might not cause problems in calculation, it creates certain inequality between ships of different sizes and types. SOLAS 2020 regulations are based on statistical data, which means that while for example R-index is different for different types and sizes of ships, it can be assumed to be equally restrictive for all, because it is based in knowledge of real cases. The deterministic approach is not based on real cases but instead on a pre-determined damage scenario. When the deterministic calculations Polar Code are combined with the results of probabilistic SOLAS calculations, difference between levels of restrictiveness is present for different ships. [16] & [18]

4.5 Solutions to improve damage stability

4.5.1 Changing main dimensions

When studying the effect of the main dimensions of the ship to the stability of the ship, equation (2) from chapter 2.2 can be expressed:

$$\boldsymbol{GM_0} = \boldsymbol{KB_0} + \boldsymbol{B_0M_0} - \boldsymbol{KG} = \boldsymbol{KB_0} + \frac{I_T}{\nabla} - \boldsymbol{KG} \tag{21}$$

Length

If only the length is increased without changing breadth or draught, $\boldsymbol{KG}$ may increase, which decreases stability. If the length is increased at the at the expense of the draught, the stability improves, except at large inclination angles.

Draught

By decreasing the draught of a ship in relation to the volume, it is possible to increase the initial stability. At the same time, the limiting angle φ_D increases, causing the ship to lose stability quickly at large angles.

Breadth

Out of the main dimension, the breadth has the most impact on the stability of the ship. Increasing the breadth will also increase the moment of inertia of the waterplane I_T.

$$I_T = \frac{2}{3}\int_0^L y^3 dx \tag{22}$$

That in turn leads to the increase of GM. The effect of breadth on stability is illustrated in figure 11. A narrower ship has a smaller radius of curvature $\boldsymbol{BM}$. The extent of the stability of the ship is limited by limiting angle ϕ_D, which corresponds with limiting point B_D. As we can see from figure 11, the narrower ship (kapea laiva) has a larger limiting angle than the wider ship (leveä laiva). When the ship inclines, its weight and buoyancy cause a righting moment, the tension indicator of which is:

$$h = \boldsymbol{KM} sin\ \phi - \boldsymbol{KG} sin\ \phi = \boldsymbol{B_0M} sin\ \phi - \boldsymbol{B_0G} sin\ \phi = \boldsymbol{GM} sin\ \phi \tag{23}$$

and thus, if the GM is same for both of the ships, the narrower ship has shorter tension indicator.

In addition to improving the stability, bigger breadth will also increase the area of the ship that can be utilized in transporting more cargo or passengers.

A downside of increasing the breadth is that the ship has more resistance to motion, which means that the ship is slower. Also, bigger resistance to motion means that the ship consumes more fuel and is therefore more expensive to operate. Other downside is that the ship might be too stable and have a strong reaction to waves. This decreases the comfort of people on board, which is a crucial factor for passenger ships.

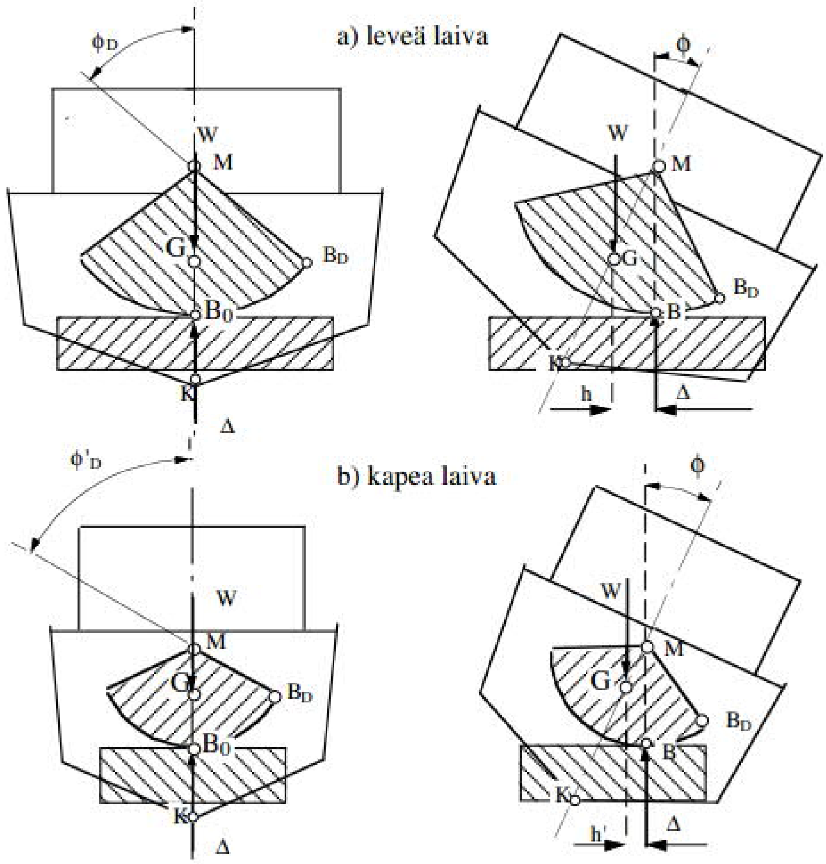


Figure 11. Effect of breadth on stability [1]

Freeboard

Freeboard is the distance between the waterline and the main watertight deck (weather deck or freeboard deck). Raising the freeboard will mean that the weather deck immerses at bigger angles. Therefore, the openings will also go underwater at bigger angles.

The effect of freeboard to stability is shown in figure 12, where two ships with equal displacements, breadths and centers of gravity, but with different freeboards ($f_2 > f_1$) are compared. The initial stability for the two ships is the same, but as we can see from figure 12, the ship with the higher freeboard will put the weather deck underwater at bigger angles and therefore be more stable of the two ships compared for the main part of the stability range.

The downside of raising the freeboard deck is that it will cause the vertical center of gravity (VCG) of the ship to also raise, which will have a negative effect on the stability of the ship. The effects to ship’s stability caused by increasing the freeboard must be considered separately for each ship.

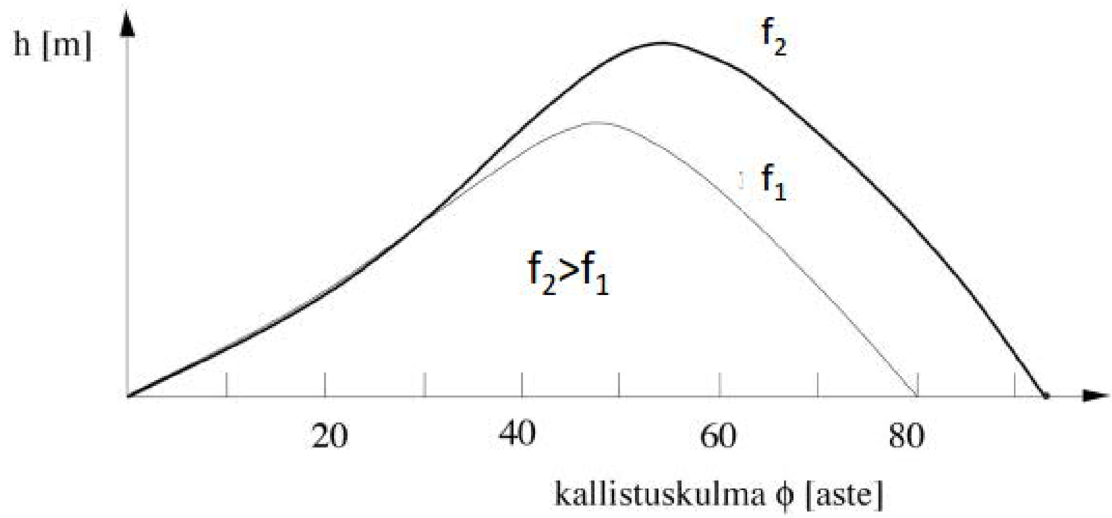


Figure 12. Effect of freeboard on stability [1]

Volume of displacement

Increasing the volume of displacement of the ship without altering the length, breadth and draught of the ship will cause the fullness of the hull to increase. This means that the VCG of the displacement lowers and stability increases.

Vertical center of gravity

Lowering the vertical center of gravity of the ship is the best way to improve the stability of the ship. With a lower VCG the metacentric height is bigger, which means that the ship is less likely to incline to the side of the damage.

The downside of lowering the VCG is that in practice, either the deckhouse must be smaller or the capacity for cargo must be decreased. In the case of passenger ships, this means that there will be less space for passengers. This means less income for the ship and therefore it is not cost-effective.

Shape of hull

The optimal shape of hull considering stability would be narrow stern and wide bow, because narrow bow immerses easily while wide stern raises easily from the water and thus decreases the stability. However, this type of hull design would not be optimal for e.g. resistance of motion. [1]

4.5.2 Optimizing subdivision and compartment connections

Bulkheads

The largest possible length of flooded compartment, floodable length, can be calculated with either added weight method or lost buoyancy method (see chapter 2.5). Vertically the flooding is assumed to reach the margin line. Margin line is a line, which the waterline of the damaged ship must not exceed and is located at least 76 mm below the edge of the bulkhead deck. Once the flooded length is calculated, it is multiplied with the subdivision index to find the permitted length of the watertight compartments.

By adding transverse bulkheads or changing the location and orientation of longitudinal bulkheads (B/5 bulkheads) it is possible to increase the A-index.

Usually in the design of the watertight subdivision of the ship, compromises have to be made. The best possible A-index might not be achievable, because the location, size and usability of storage, accommodation, equipment and structures might not allow that.

U-tanks

Tanks that go across the ship in the transversal direction reaching each side are called U-tanks. The purpose of U-tanks is that they distribute the flooded water across the ship and thus the water does not stay in on just one side of the ship. Therefore, U-tanks decrease asymmetrical distribution of weight and consequently strong heeling, thus improving the damage stability. The downside of U-tanks is that they tend to have a big volume, which means that a damage to a U-tank allows a lot of water flood in, which can impair the damage stability.

Cross-flooding

Cross-flooding means allowing the flooded water to flow into the undamaged compartment opposite the damaged compartment on the other side of the centerline. This is executed by using pipes connecting the compartments. The purpose of cross-flooding is to prevent the ship from heeling strongly to the damaged side due to asymmetrical distribution of the weight of the flooded water within the ship.

If cross-flooding pipes are used in a ship, intermediate stages of flooding must be taken into consideration. Calculation for intermediate stages must be performed whenever the complete fluid equalization is not instantaneous. Instantaneous equalization in regulation 7.2 of SOLAS Chapter II-1 is defined as equalization which is completed in less than 60 seconds. In addition to compartments connected with cross-flooding pipes, bulkheads surrounding refrigerated spaces and longitudinal bulkheads with non-watertight doors are examples of flooding situations, where equalization may take longer than 60 seconds.

When performing damage stability calculations for a ship fitted with cross-flooding devices, it is important to study the intermediate stages, not just the final stage. In the final stage, after a cross-flooding pipe has distributed flooded water from the damaged compartment to an undamaged compartment for a fluid equality, the stability may be sufficient, but that does not mean that the stability is sufficient before the equalization is completed. In the intermediate stages, the ship might have a larger heel angle than in the final stage. A large heel angle is a decreasing factor for the stability in itself and it also may cause some openings to submerge and thus decrease the stability even further. [9]

4.5.3 Other solutions

Bilge keels

Bilge keels, long and thin keels located longitudinally along the ship at bilge area, dampen the rolling motion of the ship in the waves. Bilge keels lessen the motion of the ship in regards to the waves and therefore the waves bring less water on the deck of the ship. The water-on-deck situation is governed by Stockholm Agreement and is particularly of interest for RoPax vessels, which have large undivided areas such as car decks.

For cruise ships, water-on-deck is not usually a crucial problem. Also, bilge keels are not taken into account in the damage stability regulations, so they give no benefit to the calculation of the A-index. [1]

Flooding Containment System

Traditionally, damage stability risk control options have been passive in nature, meaning design measures, such as changing the main dimensions, installing bilge keels etc. The trouble with passive protection is that it consumes deck and hull space and thus is not usually cost-effective. In 2006, the Maritime Safety Committee approved at its 82nd session guidelines on alternative designs and arrangements for chapters II-1, which deals with damage stability, and III of SOLAS. They entered into force on January 2009. The guidelines provide a legislative instrument for improving safety through active means. [31]

One of these active methods is Flooding Containment System (FCS). The functioning method of FCS is that highly expandable liquid foam is pumped into the flooded compartment after damage has happened. The foam will close openings which do not have watertight doors, reduce up-flooding, restrict the water from spreading to other compartments, form top seals and minimize free surface effects. The research done by a spinoff company of the University of Strathclyde, Maritime Safety Innovations Ltd, found that FCS improved ships' damage survivability greatly. Figure 13 shows the impact on survivability of FCS for cruise ships. [32]

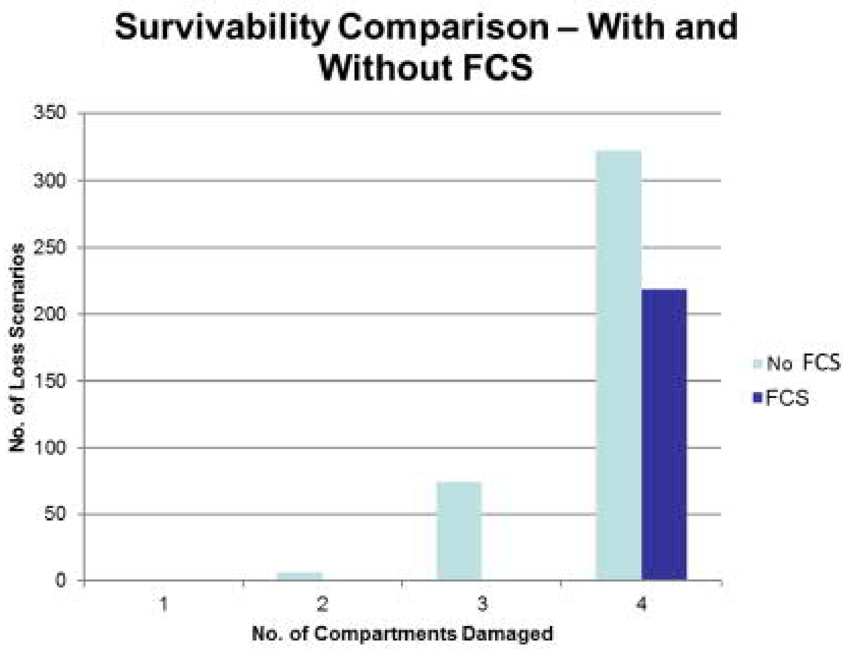


Figure 13. FCS impact on survivability for cruise ships [32]

5 Case study

5.1 Introduction of the case ship

The case ship used in this study is a small cruise ship intended for short, two-week trips in the Arctic or the Antarctic areas. As a reference for the initial design of the case ship, an already constructed ship of similar size and purpose was used. However, the reference ship was built to comply with SOLAS 2009. SOLAS 2020 and Polar Code were not considered in the design of the reference ship and therefore are not considered in the initial design of the case ship either. The aim of this study is to optimize the design to be compliant with SOLAS 2020 and Polar Code.

The case ship fulfils the requirements of International Convention of Load Lines, Intact Stability Code and MARPOL. It is designed according to good engineering customs. The general arrangement of the initial design is presented in figure 14 and appendix 1. The main particulars are shown in table 3.

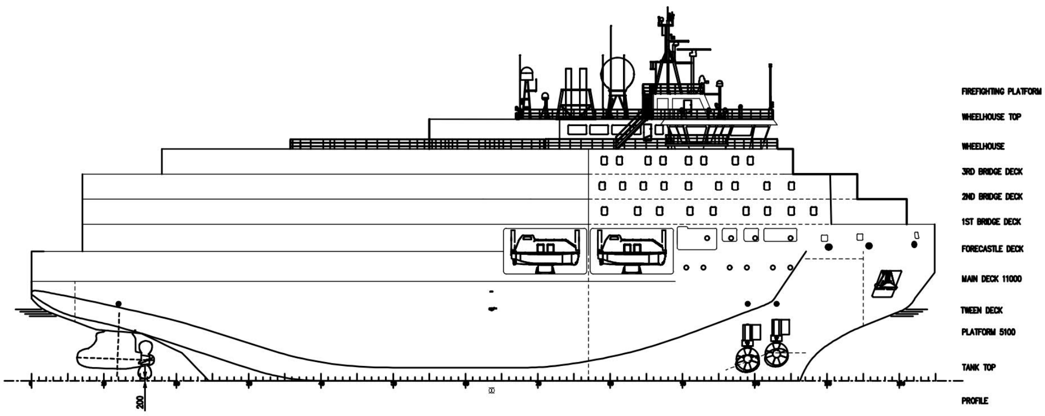


Figure 14. Profile of the case ship

Table 3. Main particulars of the case ship

Length overall	99.9 m
Length of design water line	94.0 m
Breadth	25.3 m
Draught	7.6 m
Displacement	10185 tons
Speed	16 knots
Gross tonnage	8626 tons
Number of people on board	273 persons
Ice class	PC2

The case ship has capacity for 172 passengers and 101 crew members for a total of 273 persons on board. The accommodation for crew consists of two-person cabins for most of the crew and single cabins for the higher-ranking members of the crew. All the passenger cabins are two-person cabins. For the passengers, there are restaurants, cafes, clubs, spas, a gym and a casino.

The case ship is meant for 14-day operation at an operation speed of 16 knots to offer scenic cruises at polar waters. There are four main engines, which use Marine Diesel Oil (MDO) as fuel. The ship has enough fuel capacity for 30-day operation at the economical speed of 12 knots with a 10% reserve. There is also enough provision for 30 days. The ship's capacity for fresh water corresponds with 4.5 days of normal usage, and the ship is equipped with machinery to convert sea water into fresh water.

To calculate the wind moment, a wind profile (figure 15) was created. Its center of gravity and the area limited by it give an adequate approximation of the shape of the hull and the deck structures. Projections, such as the axels of the propellers were not modelled and do not show up in the wind profile either.

Figure 15. Wind profile

For the damage stability calculations, three initial conditions were defined as required in SOLAS 2009 and 2020. These initial conditions are initial conditions in deepest subdivision draught (DS), in light service draught (DL) and in partial subdivision draught (DP).

Deepest subdivision draught is the waterline, which corresponds to the summer scantling draught of the ship. Light service draught is the service draught of the ship with all passengers, crew and their effects, 10% of the consumables and enough ballast for stability and trim. Partial subdivision draught is the draught that is obtained by adding 60% of the difference between DS and DL to the light service draught. The initial conditions are presented in table 4. For all the initial conditions, the trim is zero.

Table 4. Initial conditions

	T[m]	GM[m]
DS	7.90	1.45
DP	7.26	1.25
DL	6.30	1.30

5.2 Research method

The main tool used in this study is NAPA (Naval Architecture Package). NAPA is a software, which allows ship designers to define for example the geometry, hydrodynamic properties, hydrostatic properties and stability of a ship. In this thesis, special interest is on damage stability module, with geometry and loading condition modules also used. The damage stability calculation was executed using NAPA Manager -tool. In this thesis, the shape of the hull and the arrangement of the spaces with the watertight boundaries were defined using NAPA software. The NAPA model for the initial design is presented in appendix 2. Because the watertight bulkheads do not reach above the main deck (deck 4) the arrangement of the spaces in decks from 4 up do not affect stability. The case ship has been modelled in NAPA with detail up to deck 4. Above that, correct sized space reservations with their general purpose were modelled, but with less detail (e.g. cabins are not individually modelled). The arrangements in decks below deck 4 are presented in connection with each case.

Openings were defined in NAPA Manager and used in damage stability calculation. At the final stage of any given damage the ship is not assumed to heel more than 7 degrees. Therefore defining the opening seems irrelevant as they are not in any danger of submerging. However, at the intermediate stages of some damage cases the ship may heel to over 7-degree angle and thus the openings may affect the s-factor through disrupting the GZ-curve. Openings are presented in appendix 3.

Damages were created and their A-indices were calculated in NAPA Manager. NAPA Manager uses SOLAS 2009 rules in the calculation of A-index, but because it is the same for cruise ships in SOLAS 2020, the results can be used here. Damages were created up to 7-zone damages, because in the case of the ship in this study, 7-zone damages affect the third decimal of the A-index and the required index R is defined with three decimals (0.722). After the A-index was calculated, individual cases contributing the index could be observed in the Analysis-part of NAPA Manager. Therefore, compartments and groups of compartments with the weakest A-index could be found and focused on in the improvement of the design.

Damages caused by the ice were created by a macro within NAPA, which created ball-shaped damages with a radius of 760 mm. Thus, the transversal extent of the damage was correct for all the damages and the extent was always measured normal to the shell, even at the curved parts of the ship (i.e. bow and stern). Horizontally, the damages were created at the middle and at the end of each compartment both on the sides and on the bottom. Vertically, the damages were created at the waterline and at the vertical ends of the compartments below the waterline. These principles of creating damages was used in order to take into account both single- and multiple-compartment damages. After the damages were created by the macro, they were manually checked for the two instances where the macro would give incorrect results. These instances are: 1) If, forward from the maximum breadth of the UIWL, the length of a compartment was less than 4.5% of UIWL (4.23 m), a three-compartment damage needed to be added and 2) If the length of a compartment at other areas was less than the diameter of the damage-ball (1.52 m) but more than 1.5% of UIWL (1.41 m). a three-compartment damage needed to be removed. These corrections were made by hand. The ice damages were created separately for each case. The ice damages for the initial design, as created by the macro, are pictured in figure 16.

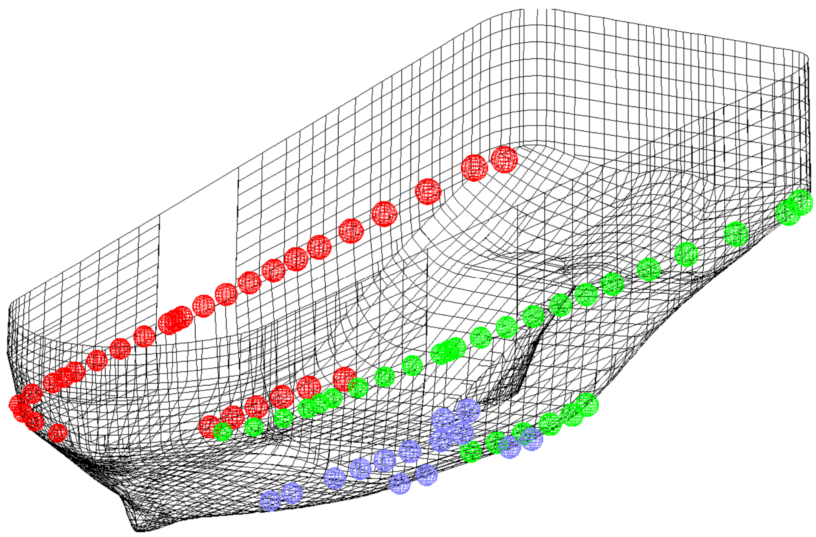
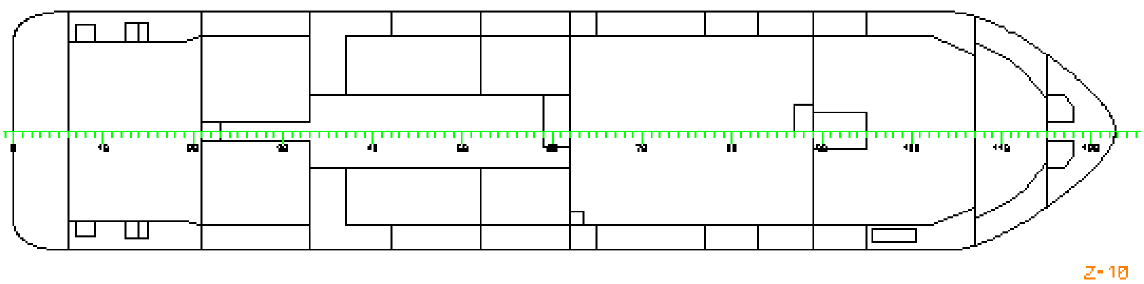


Figure 16. Damages caused by ice according to Polar Code

In this study, three methods of improving damage stability were used: changing the arrangement of U-tanks, modifying the subdivision and using cross-flooding devices. Other methods are introduced in chapter 4.5, many of which are not practical either because they require major changes in the design (i.e. changing the main dimensions) or are not recognized by the rules as a method to improve stability (i.e. bilge keels).

5.3 Case 1: Initial design

As mentioned in chapter 5.1, the initial design of the case ship is made to comply to SOLAS 2009, not SOLAS 2020 or Polar Code. However, in the initial design, optimal design for the damage stability was already considered by maximizing symmetry. This was done by using U-tanks and balancing the sizes and locations of smaller tanks. When possible, the tanks opposite each other are identical in purpose as well as size, otherwise voids were used. Also, the continuity of structures was taken into account when considering the placement of the bulkheads. The compartment limits below the freeboard deck are shown in figure 17.



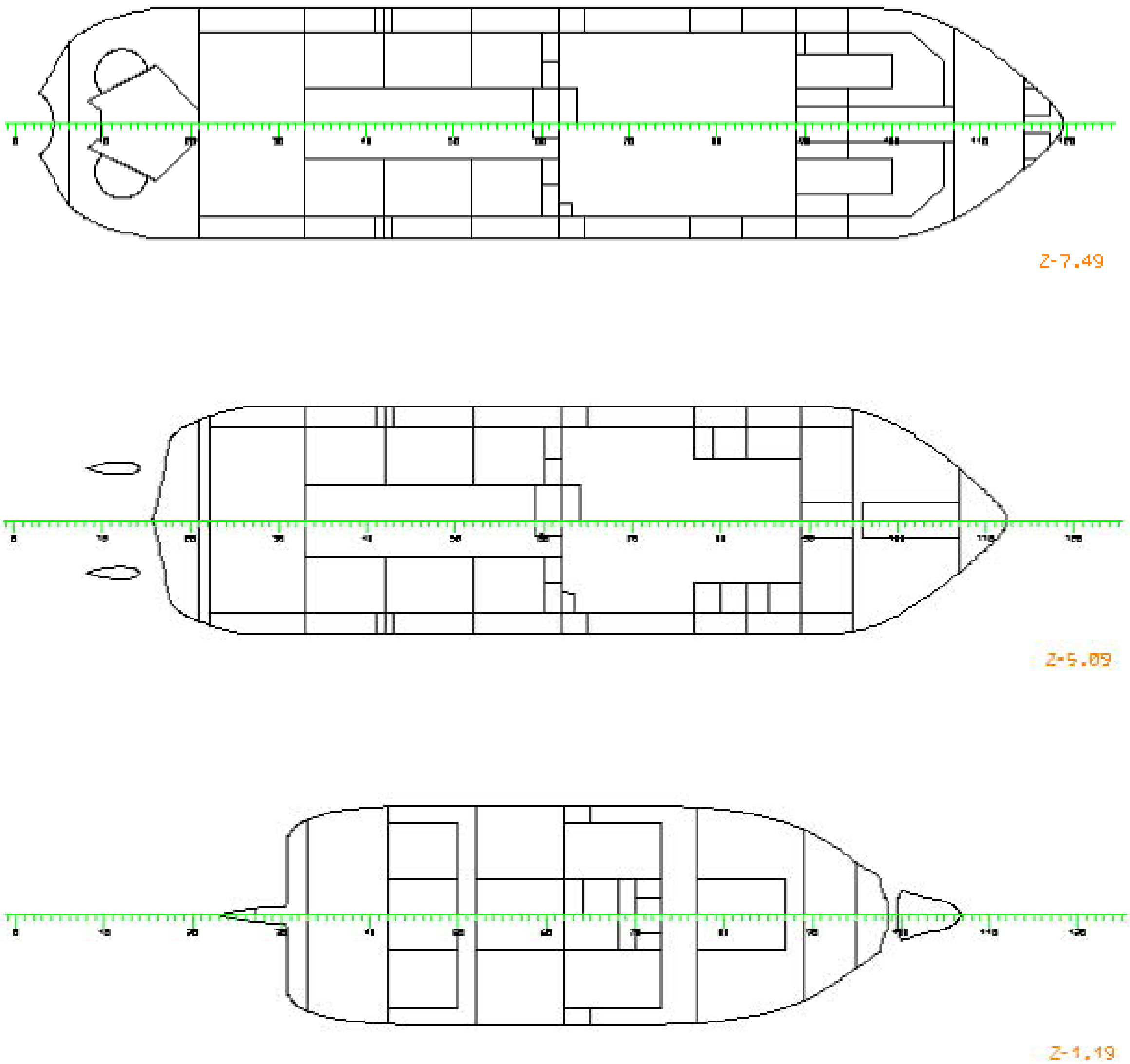


Figure 17. Compartment limits below deck 4

For the initial design, the attained index A is 0.69265. The required index R according to SOLAS 2020 is 0.722. All the damages caused by the except for one (figure 18) satisfied the Polar Code -requirement of s = 1.

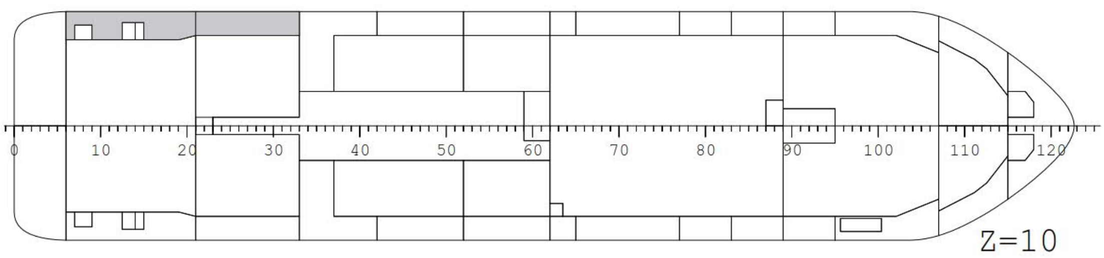


Figure 18. Ice damage with s < 1

5.4 Case 2: U-tanks

Adding U-tanks can improve the damage stability of a ship by distributing the flooded water symmetrically across the centerline. To see the effect of U-tanks, a design which is identical to the initial design above double bottom (figure 17) but has more U-tanks in the double bottom, was created. The U-tanks were also placed so that at least every second tank in the longitudinal direction was a U-tank. The compartment limits in the double bottom are shown in figure 19.

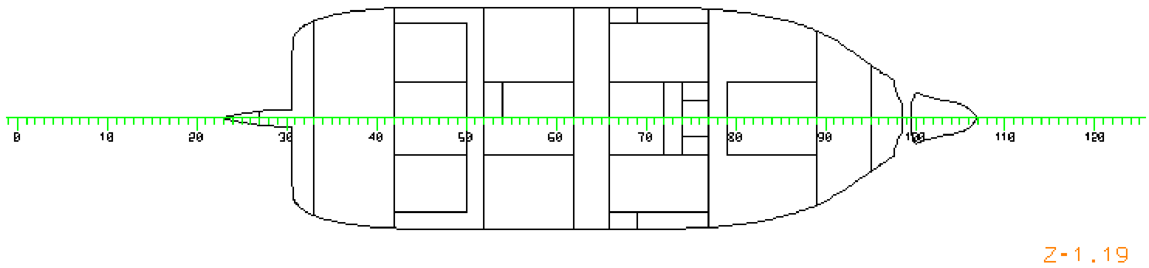
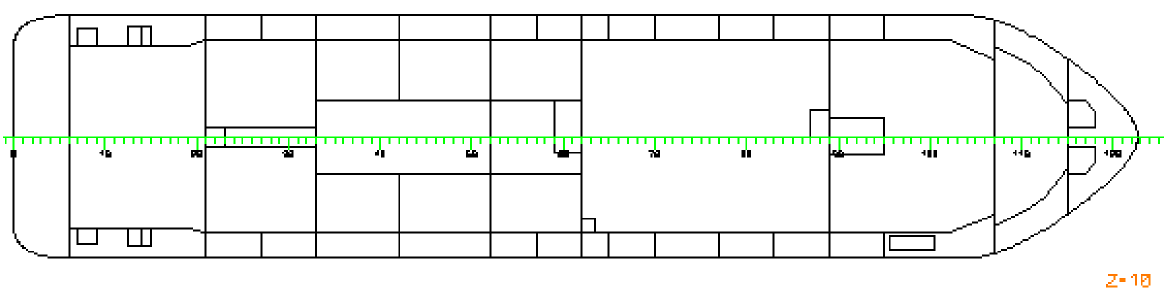


Figure 19. Compartment limits in the double bottom

The attained index A is 0.69433, which offers only marginal improvement to the initial design, where A = 0.69265. As in the initial design, all damages caused by ice but one had s = 1.

5.5 Case 3: Denser transversal subdivision

Because the A-index achieved with the initial design was not sufficient to satisfy SOLAS 2020 damage stability regulations, a new design with denser subdivision below deck 4 was created. The general arrangement went through two incarnations named versions A and B of case 3 (appendix 4), before a design with a sufficient A-index was found (figure 20). Watertight transversal bulkheads were added astern of the ship and compartment limits were adjusted for the new subdivision.



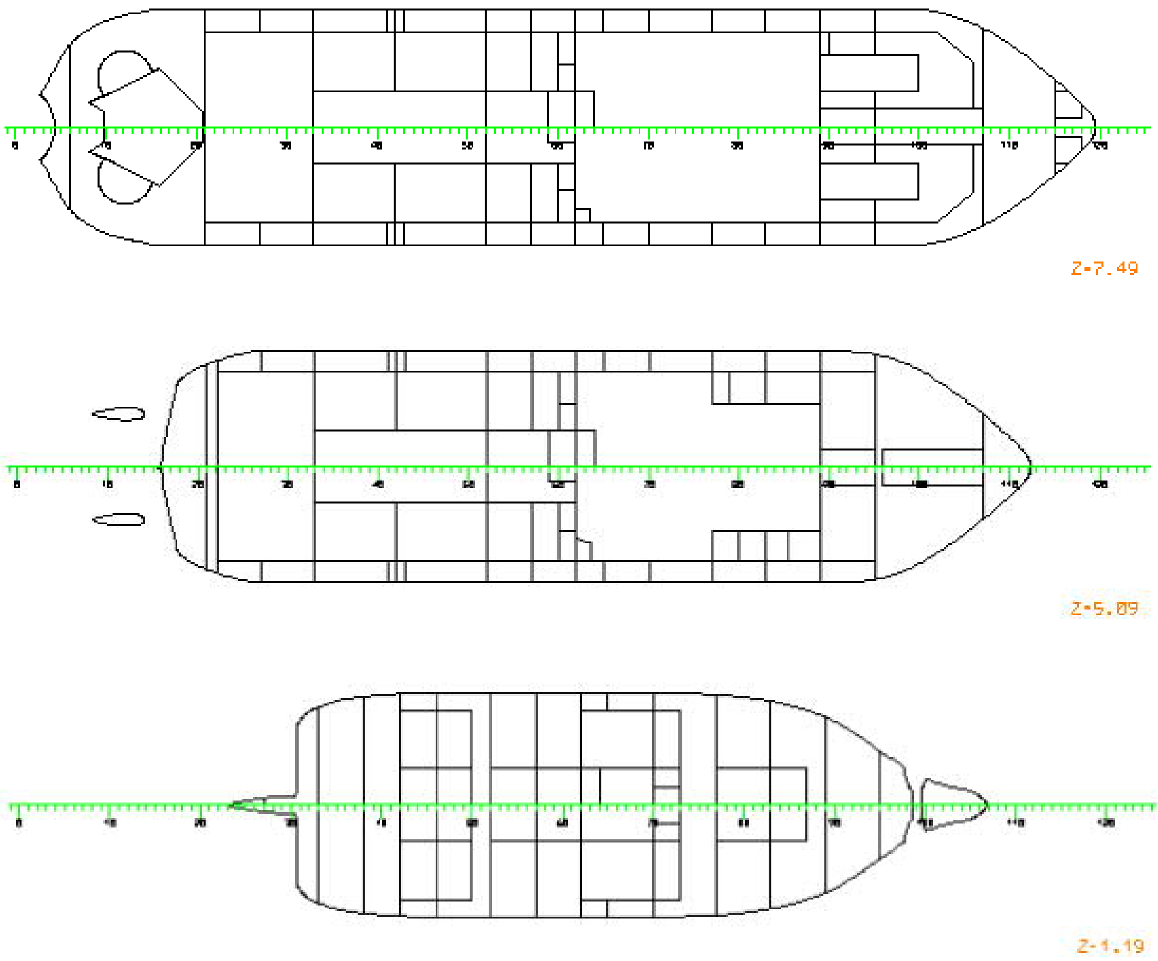


Figure 20. Compartment limits below deck 4

In general, transversal bulkheads were added at areas where the potential A-index and the achieved A-index differed the most. However, there are three exceptions. Firstly, the roll reduction tanks were not divided with these bulkheads, because their structural requirements, e.g. connection to air channels, did not allow that. Secondly, at the bow area, addition of subdivision was moderate, so that the length of the compartment would not be less than the longitudinal ice damage according to Polar Code. Thirdly, one of the areas, where the A-index in the initial design most differed from its potential was between frames #62 and #89, due to the big undivided area at that stretch (figures 17 and 20). However, the area could not be divided with transversal bulkheads, as it contains the pump room and the engine room, where space for the machinery is required.

The attained index A for the new design is 0.72598, which is above the R-index stated in SOLAS 2020. The design also complies with the damage stability rules of Polar Code, as for all ice damages s = 1.

5.6 Case 4: Cross-flooding

As seen from figure 20, trying to achieve an A-index sufficient for SOLAS 2020 requirements with just modifications to the subdivision leads to a very fragmented tank plan, which is not practical. Therefore, other methods to improve damage stability were needed. Adding cross-flooding devices was chosen as a solution, because it is a method that has been widely used and found effective and does not require major structural changes of the ship. At first, the effect of cross-flooding devices was observed by calculating stability for a design, which was otherwise identical to the initial design (figure 17), but with cross-flooding pipes added between tanks in the double-bottom. In figure 21, red dots are the ends of cross-flooding pipes. Each pipe connects tanks opposite each other across the centerline of the ship. The cross-flooding pipes all have a diameter of 0.7 m. With these pipes, a complete fluid equalization can be achieved in less than 10 minutes. Therefore, according to regulation 7.2 of SOLAS chapter II-1, the survivability factor for passenger ships can be assumed as the smallest values of $s_{intermediate}$ or s_{final}. The equalization takes longer than 60 seconds, so it cannot be assumed instantaneous and intermediate stages are calculated.

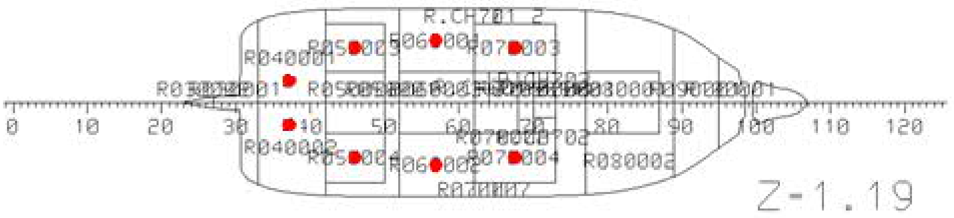
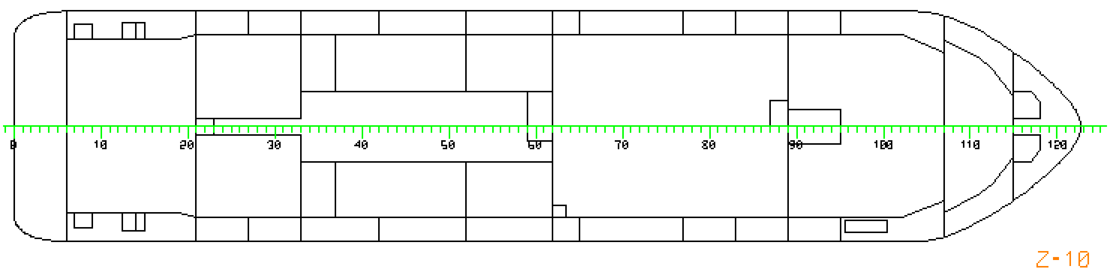


Figure 21. Cross-flooding pipes

With these added pipes, the attained index A was 0.7142, which is a clear improvement to the initial design, where A = 0.69265, but not adequate for SOLAS 2020. Also, the requirements of Polar Code are not met, as one of the ice damages (same as with initial design, see figure 18) has s < 1.

5.7 Case 5: Final design

As the A-index achieved with just a few cross-flooding pipes was very close to the required index R, only minor changes to the subdivision were needed to the additional improvement of the damage stability. The changes are shown in figures 22 and 23.



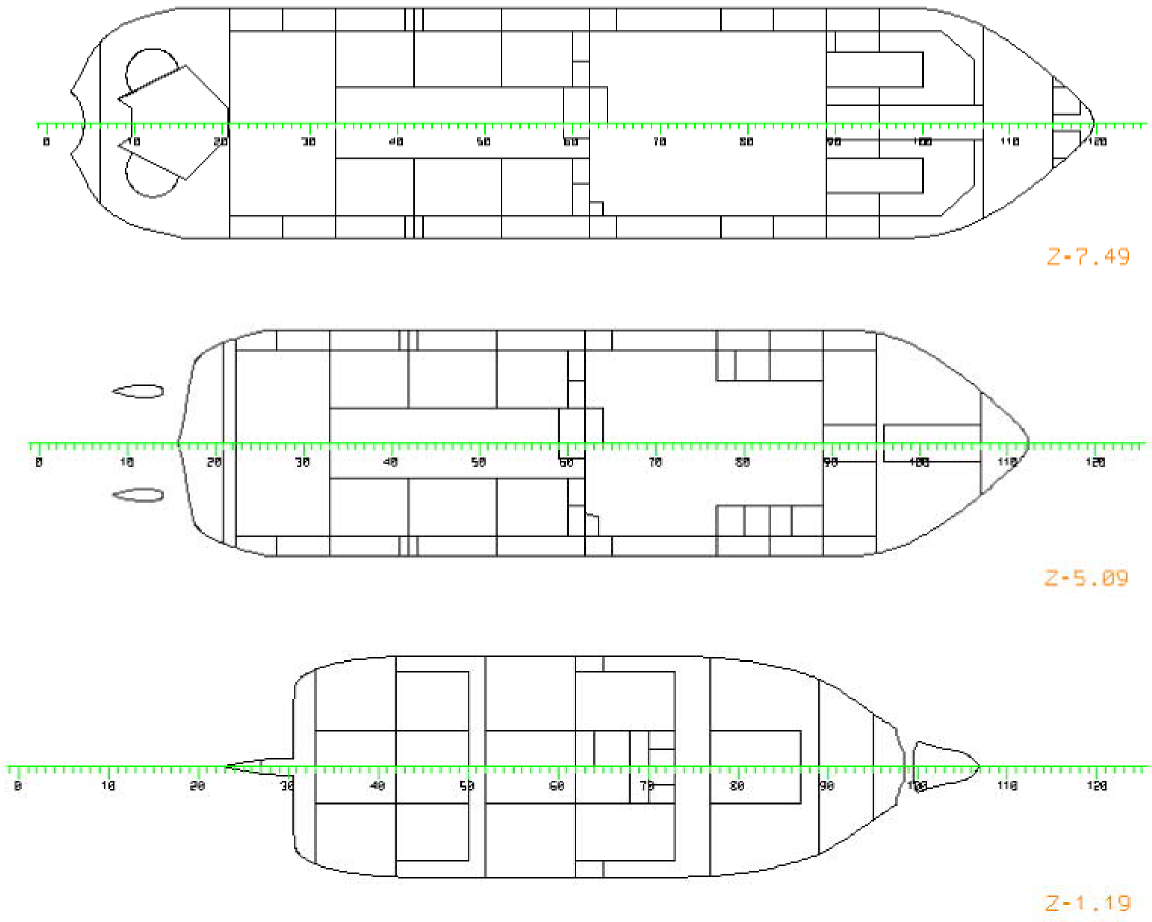


Figure 22. Compartment limits below deck 4

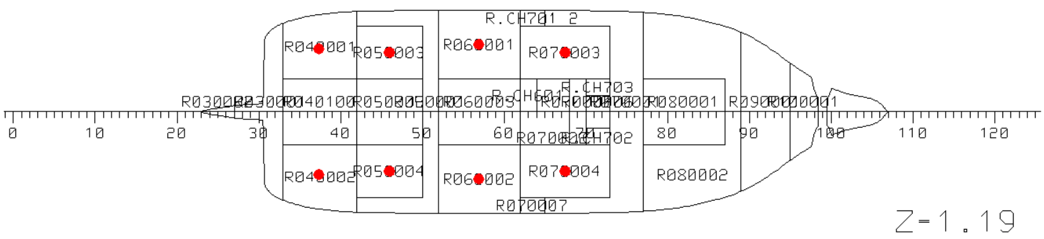


Figure 23. Cross-flooding pipes

A transversal bulkhead was added at frame #27, a longitudinal bulkhead was added between frames #33 and #37 at deck 3 and the continuity of structures was better followed by dividing the ballast tanks at frames #33 - #42 to three instead of two tanks and placing a cross-flooding pipe between them.

With these changes both the damage stability regulations of SOLAS 2020 and those of Polar Code were satisfied as A = 0.72508 and for all ice damages s = 1.

6 Analysis of the results

6.1 Case-specific analysis

6.1.1 Case 1: Initial design

SOLAS 2020: not fulfilled (A = 0.69265)

Polar Code: not fulfilled (one damage, where s < 1)

The A-index of the initial design falls nearly 0.03 short of the R-index defined in SOLAS 2020. This is not surprising, as the initial design is based on similar ships designed previously to satisfy the requirements of SOLAS 20009, where the required index R is smaller.

While Polar Code was not considered in the initial design, only one of the damages caused by the ice did not fulfil its damage stability regulations. This would indicate that the implementation of Polar Code will not cause difficulty in the design.

6.1.2 Case 2: U-tanks

SOLAS 2020: not fulfilled (A = 0.69433)

Polar Code: not fulfilled (one damage, where s < 1)

The addition and new placement of U-tanks does not significantly improve the damage stability. The difference between the A-indices of case 1 and case 2 is in the third decimal. The reason behind such a small improvement is likely to be that even though the U-tanks distribute the flooded water more evenly across the ship, they also allow more water to enter the ship. The added weight partially negates the effects of the more symmetrical weight distribution.

Polar Code requires s to be equal to one for all loading conditions, meaning basically that the angle of heel cannot exceed 7°. Therefore, U-tanks would be useful in regards to Polar Code, because they reduce unsymmetrical flooding and thus also reduce heeling. However, because the initial design was already nearly adequate for Polar Code -requirements, the additional U-tanks bring no practical improvement. The only damage, which does not satisfy the damage stability regulations of Polar Code is damage to tanks, which do not reach double bottom and cannot be transformed to U-tanks.

Because the achieved benefits in the A-index were minimal and no improvement was seen regarding Polar Code, addition of U-tanks is not a practical solution in the improvement of damage stability.

6.1.3 Case 3: Denser transversal subdivision

SOLAS 2020: fulfilled (A = 0.72598)

Polar Code: fulfilled (s = 1 for all loading conditions)

An A-index bigger than the R-index required by SOLAS 2020 could be achieved by dividing nearly all tanks in the double bottom, and majority of the tanks at the sides, in half. Also, two of the tanks not in contact with the shell needed to be halved. This means that major changes in the subdivision were required to increase the A-index of the initial design by the 0.03 that it was lacking.

As for the Polar Code requirements, no additional measures were needed to fulfil them. The added subdivision required to satisfy SOLAS 2020 automatically removed the only issue with the ice damages in the initial design. The only ice damage, which had s < 1, was no longer a problem because the compartments it concerned had been divided in half, thus allowing lesser volume of flooded water to enter the ship.

While the new damage stability requirements could be fulfilled with denser transversal subdivision and the design could be realized, it might not be the most practical solution. A great number of bulkheads needed to be added resulting to a garbled general arrangement.

6.1.4 Case 4: Cross-flooding

SOLAS 2020: not fulfilled (A = 0.7142)

Polar Code: not fulfilled (one damage, where s < 1)

The damage stability requirements of SOLAS 2020 were not fulfilled - but almost, as the A-index was only 0.0078 below the requires index R. This was achieved by only adding four cross-flooding pipes in the double bottom of the ship. Otherwise the design was identical to the initial design, where A-index was more than 0.02 smaller.

Again, only one damage does not satisfy the requirements of Polar Code. This damage, same as in cases 1 and 2, is located at compartments on the level of deck 3. Adding cross-flooding pipes would not be practical due to the location of the damaged compartments. More sensible solution is to revise the subdivision at that particular location.

6.1.5 Case 5: Final design

SOLAS 2020: fulfilled (A = 0.72508)

Polar Code: fulfilled (s = 1 for all loading conditions)

With just a few changes to the subdivision and new placement for one of the cross-flooding pipes, SOLAS 2020 damage stability regulations could be easily fulfilled. The general arrangement is clear and organized.

Polar Code requirements could also be easily fulfilled by adding just one transversal bulkhead near the stern.

The design of case 5 was chosen as the final design, because it complies with both the damage stability regulations of SOLAS 2020 and those of Polar Code. Also, case 5 is superior to case 3 (which also satisfies these regulations), in that the design is less complicated and therefore more practical.

6.1.6 Conclusion and comparison of cases

In SOLAS 2020, for cruise ships with less than 400 people on board, the required index R is a constant 0.722. The case ship in this thesis has a total of 273 people on board, with lifeboats provided for 272 persons. Therefore, according to SOLAS 2009, the required index is R =

0.688 (equation (11), chapter 3.2.4). The new R-index is difficult to achieve, which is understandable since the R-index in SOLAS 2020 is 5% bigger than the R-index in SOLAS 2009 for this case ship. All the cases in this thesis, including the initial design (case 1) and versions A and B of case 3 (see appendix 4) have a high enough A-index for SOLAS 2009. Only two of the cases, case 3 and case 5 have an A-index higher than the R-index in SOLAS 2020.

The damage stability regulations of Polar code were easy to obey. In all the cases studied in this thesis, either one or none of the damages caused by ice fell short of the requirements of Polar Code. Because the case ship has flat sides, in most of the ship the longitudinal extent of the damage caused by ice was 1.5% of the UIWL. All compartments, except the two air channels on each side located next to each other, were longer than the extent of the damage. This means that the only three-compartment damages were ones that involved two air channels and one other compartment. Because of the small volume of the air channels, these three-compartment damages were not crucial to the s-factor. Due to the flat sides of the ship, only a couple compartments were centred forward of the maximum breadth of the UIWL. These compartments were longer than the longitudinal extent of the ice damage there, 4.5% of the UIWL. Therefore, at that area there was no three-compartment damages. A ship with more curved sides might have more problems with Polar Code, as more compartments would be located forward from the maximum breadth of the UIWL.

Optimal solution was found by using cross-flooding pipes as the main method and complementing that with minor changes to the subdivision at specific locations, where the achieved A-index was the furthest away from its potential. The fact that the addition of cross-flooding pipes to certain tanks had far greater effect than halving them with a bulkhead would suggest that the location of the flooded water inside the ship is more important to the damage stability than the amount of the flooded water. However, the amount of flooded water cannot be forgotten, because the additional U-tanks did not have the same effect as the cross-flooding pipes. The U-tanks, which go across the whole ship, take in more water than two tanks of a three-tank row across the ship. Also, in the case of a U-tank, the water floods first to the damaged side, then to the middle and last to the undamaged side. In case of two tanks on the sides connected with a cross-flooding pipe, the water floods first to the damaged side and then to the undamaged side, allowing the fluid equalization be more balanced than with U-tanks.

6.2 Sensitivity analysis

Sensitivity analysis is used to study how sensitive the results obtained by a model are for the changing of starting values and hypotheses. Analysis is executed by using variables, which are assumed to have significant effect on the result. First, the variables are changed one at a time while other variables are kept same to see the effect of an individual variable. Then, all the variables are set in their extreme values to observe the combined effect of the variables. The reason for doing sensitivity analysis is to find out how the uncertainty of the starting values affects the final results.

For this case study, the most significant starting values are considered to be the trim and the vertical centre of gravity of the ship's lightweight. Their effect is observed by changing their value +/-0.1 m from the values used in calculation within the case study. The sensitivity analysis is performed for the final design (case 5). The effect of changing the values is studied through comparing the changes in the total A-index, the A-index of a fully loaded ship (initial condition DS) and the required minimum GM. The results of the sensitivity analysis are shown in tables 5 and 6.

Table 5. Results of the sensitivity analysis

Case	**A-index**		**minGM**	
	Total	**DS**	**SOLAS 2020**	**SOLAS 2009**
Original	0.72508	0.71679	1.437	1.313
C1	0.70129	0.70325	1.420	1.317
C2	0.74942	0.73346	1.436	1.313
C3	0.72442	0.71682	1.439	1.312
C4	0.72571	0.71685	1.434	1.312
C5	0.70047	0.70171	1.415	1.317
C6	0.74907	0.74131	1.455	1.326

Table 6. Results of the sensitivity analysis as per cents

Case	**A-index**		**minGM**	
	Total	**DS**	**SOLAS 2020**	**SOLAS 2009**
C1	-3.28 %	-1.89 %	-1.18 %	+0.30 %
C2	+3.36 %	+2.33 %	-0.07 %	0.00 %
C3	-0.09 %	0.00 %	+0.14 %	-0.08 %
C4	+0.09 %	+0.01 %	-0.21 %	-0.08 %
C5	-3.39 %	-2.10 %	-1.53 %	+0.30 %
C6	+3.31 %	+3.42 %	+1.25 %	+0.99 %

In case C1, the VCG of the ship's lightweight is raised 0.1 m and in C2 lowered 0.1 m. In case C3 the trim is 0.1 m and in C4 -0.1 m. In C5, both the VCG and the trim are set at +0.1 m. In case C6, both of the values are -0.1 m.

From the results it can be seen that the A-index is most affected by the change in the VCG of the ship's lightweight. Increasing the VCG by 0.1 m decreases the total A-index by over 3% and decreasing the VCG causes also over 3% change, but to the opposite direction. Changing the trim by 0.1 m changes the A-index only by 0.09%.

The biggest change in the required minimum GM is seen in case C1. Raising the VCG by 0.1 m causes over 1% decrease for the minimum GM in SOLAS 2020 requirements and nearly third of a per cent increase in SOLAS 2009 requirements.

The required minimum GM in SOLAS 2009 changes the least, with all of the variation being less than 1%. The most affected result is the total A-index, which in four of the six cases varies more than three per cents of the original results. The biggest changes happen naturally at cases C5 and C6, where both the VCG and the trim increased or decreased. The largest deviation (3.42%) is in the partial A-index when the VCG and the trim are both decreased by 0.1 m.

In general, the minimum GM is less affected by the changes in the initial conditions than the A-index. Results to the minimum GM calculated with SOLAS 2009 requirements are considerably less sensitive to the uncertainty of initial conditions than the results calculated with SOLAS 2020.

7 Conclusion

In this thesis, a cruise ship, complying with the damage stability regulations of both the upcoming SOLAS 2020 and the newly implemented Polar Code, was designed. The case ship was a modern cruise ship carrying 273 people and operating in polar waters. The subdivision of the initial design was based on similar ships of similar purpose previously designed to comply with SOLAS 2009. The optimal design was found by iterating the initial design through the use of subdivision, U-tanks and cross-flooding as solutions for sufficient damage stability.

The results of the case study indicate that the best solution is to have three tanks next to each other transversally across the ship in the double bottom. The two tanks on the sides of the ship of the three-tank row should be connected with cross-flooding pipes. In that way, symmetrical distribution of flooded water is ensured, while the intake of too much of the flooded water is avoided. U-tanks would also distribute the added weight of the flooded water evenly, but they would have to take more water in. Denser subdivision would limit the intake of flooded water, but have the added weight distributed asymmetrically. The three-tank arrangement with cross-flooding pipes is therefore the best solution. Symmetry seems to be the biggest factor in complying with the damage stability regulations of both SOLAS 2020 and Polar Code. The symmetrical distribution of added weight is a positive influence to the A-index and also prevents the ship from heeling over the limits dictated by Polar Code. While sufficient damage stability could be achieved with just denser transversal subdivision, it was found that using only alterations to subdivision as an overall solution was not practical. Added bulkheads worked better as individual corrections to complement the use of cross-flooding as the main design solution. The straight sides of the case ship seemed to help with the compliance with Polar Code, since they meant that for most of the ship, the length of the ice damages was considered to be the shorter of the two options. The damage stability regulations of SOLAS 2020 were more limiting and causing more changes to the design than those of Polar Code.

SOLAS 2020 has considerably higher R-index for passenger ships than SOLAS 2009. The change in the R-index affects especially cruise ships and raise their safety considerably. RoPax vessels have to comply with the Stockholm Agreement, which has through water-on-deck requirements set higher standards for damage stability than SOLAS, and thus they were already designed with higher A-index than SOLAS required. Cruise ships do not need to consider water-on-deck situations and therefore a change to a higher R-index is a bigger adjustment for cruise ships.

Other factor that improves safety in SOLAS 2020 is that the number of seats in lifeboats in relation to number of passengers no longer affects the index. This enables the use of modern marine evacuation systems (MES), such as using an inflatable slide to evacuate passengers straight to life rafts. MES makes evacuation faster not only when the ship is flooding, but in other emergencies, such as fire.

For smaller cruise ships with less than 400 people on board, such as the case ship on this study, perhaps the most interesting change is that R is constant. This brings added challenge to smaller ships, because in SOLAS 2009 less people on board meant a smaller R-index. According to the new regulations, a cruise ship with for example 100 passengers will have the same required R-index than a cruise ship with 300 passengers. Also, the number of passengers is the only determining variable in the calculation of the R-index. The length of the ship is not considered in the calculation of the R-index in SOLAS 2020. This is also an added disadvantage for smaller cruise ships. Previously, the shorter the ship was, the smaller the R-index was. With the new regulations, designing a smaller ship will bring no relief to the R-index.

The damage stability regulations of Polar Code provide more safety along with more design challenges to ships operating in polar waters. As a completely new set of rules, Polar Code forces designers to consider cases they have not previously needed to deal with, such as the angle of heel caused by ice damages.

While the case study in this thesis gives an indication of how the new damage stability regulations will affect the design of small cruise ships, it must be noted, that only one case ship was studied and therefore the results are not statistically significant. For better understanding, more ships with different hull shapes and main dimensions should be studied. Also, to get a better overall view and to have comparison for the smaller ships, the effect of the regulations on cruise ships with more than 400 passengers should be investigated. This would show in practice whether the new regulations benefit ships of certain length or ships carrying certain number of passengers. The effect of Polar Code and whether it is a more limiting factor for different sized ships would also be interesting to study.

8 Reflection

There is still need for more research to the calculation of the R-index and the damage stability of passenger ships in general. The probabilistic method of calculation adopted in SOLAS 2009 and also used in SOLAS 2020 is more realistic than the previously used deterministic method. However, the safety level indicated by SOLAS is considerably different to the safety level found with numerical simulations and in real case experiences. In the last 20 years, the research concerning damage stability has focused on RoPax. Therefore, the applicability of the s-factor for cruise ships is questionable. Despite the differences between RoPax and cruise ships, one level of R is defined for all passenger ships. For better damage stability regulation, quantification of real safety level for cruise ships is needed.

SOLAS has several simplifications, which affect its ability to reflect real-life situations. These simplifications are for example that grounding is not included in the attained index and the probability of sea state is not considered. Also, complex subdivision is not covered by actual s-factor. To improve the damage stability regulations of SOLAS, impact of the aspects described above should be quantified, preparation to apply first-principle methods should be done and methodology to use numerical simulations should be created.

Polar Code, due to being very new and not having many references in real life, is still lacking in many respects. Damage stability rules can be interpreted in different ways. Overall, Polar Code has issues with consistency of the precision of the rules, which makes interpretation more difficult. Also, Polar Code is missing some important parts and is vague in regards to some. While the missing or vague parts might not be directly related to the damage stability, they indicate that Polar Code is still a work in progress.

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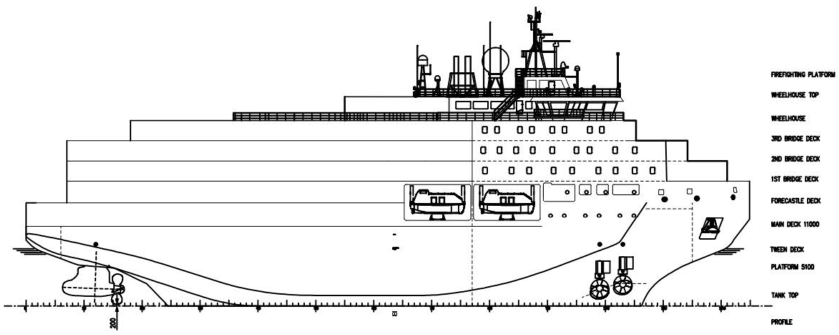
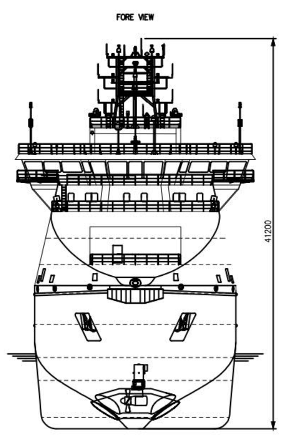
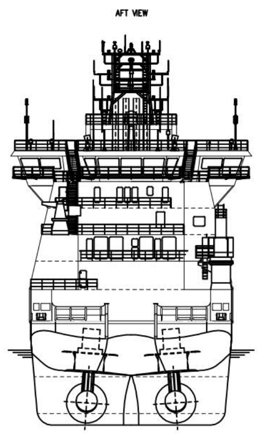
List of appendices

Appendix 1. General arrangement

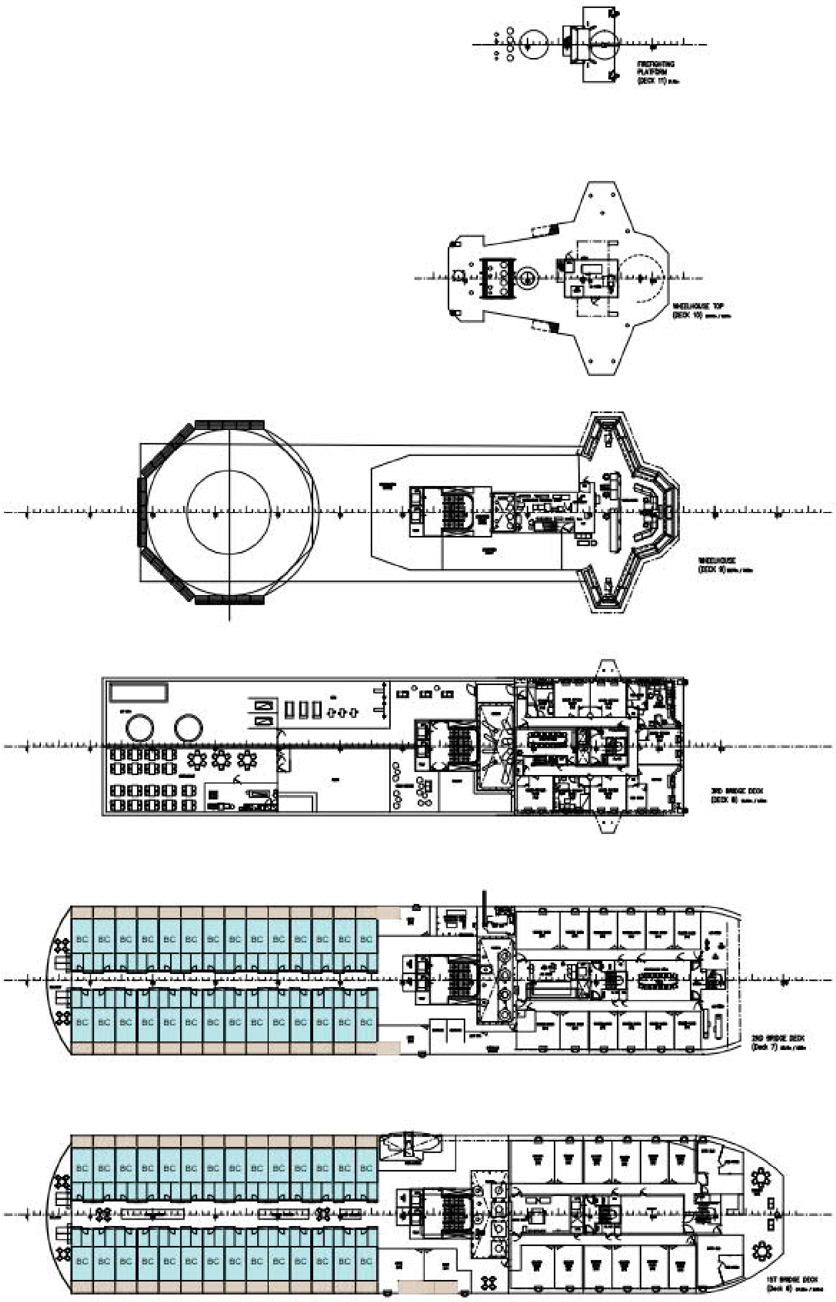


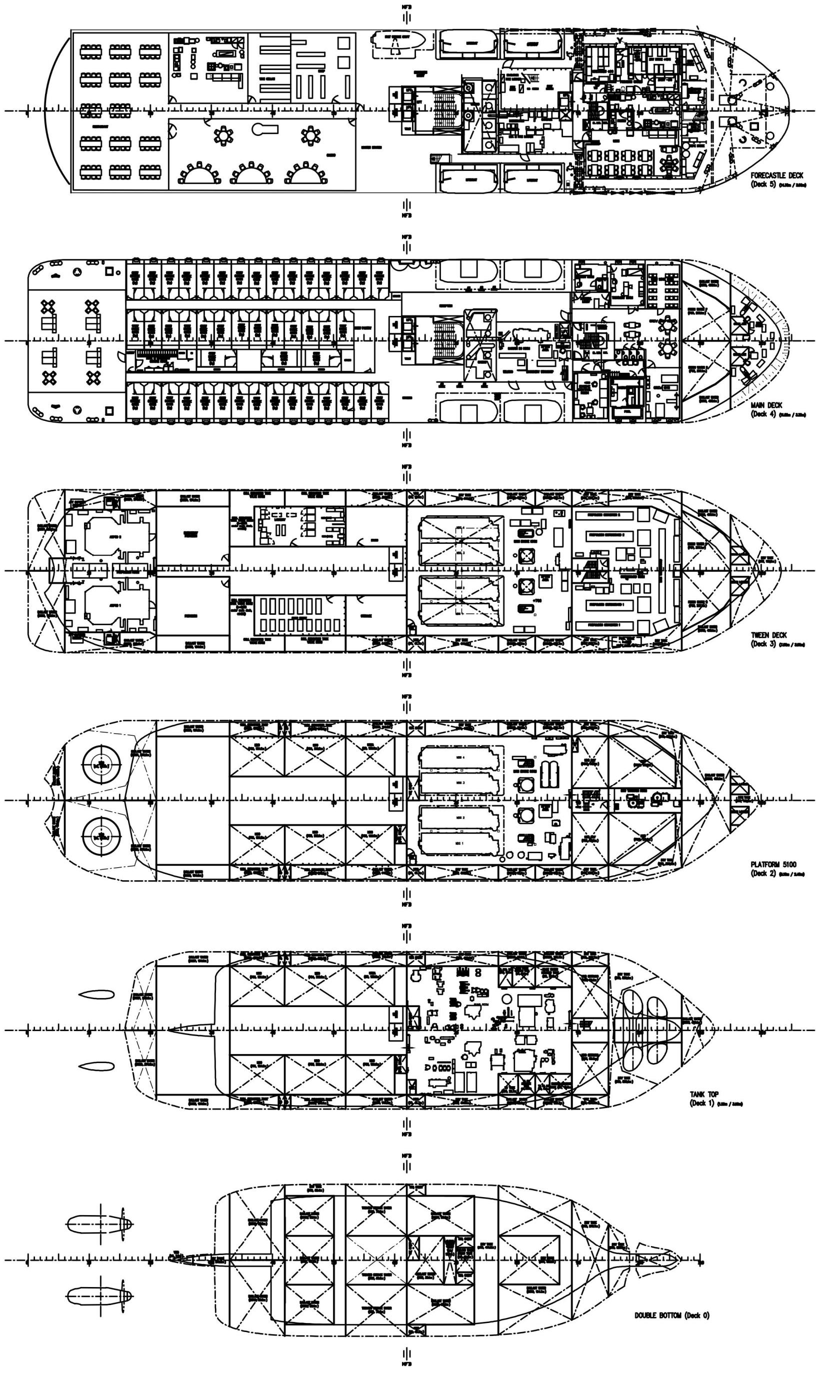




CRUISE SHIP

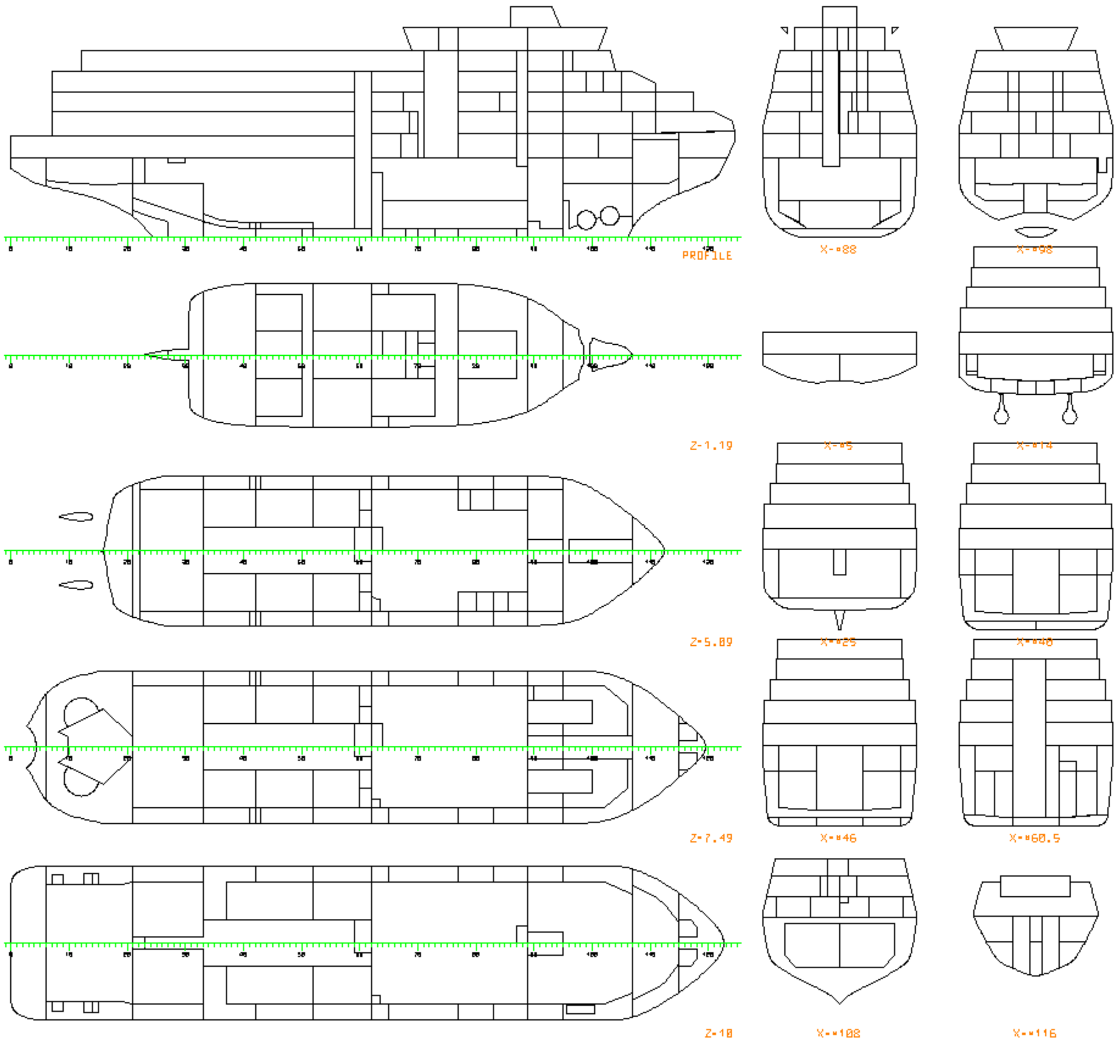
LENGTH	OVER ALL	abt.	99.9 m
LENGTH	DWL	abt.	94.0 m
BREADTH	DWL	abt.	21.0 m
BREADTH	MAX	abt.	25.3 m
DRAUGHT	DWL		7.60 m
DRAUGHT	SCANTLING, SUMMER		7.90 m
DEPTH	TO MAIN DECK		11.00 m
POWER	PROPULSION		2*6500 kW
POWER	BOW THRUSTERS		2*1500 kW
POWER	MAIN ENGINES		4*5220 kW
SPEED	DWL		16 kn
ENDURANCE	FULL SPEED		14 days
ENDURANCE	ECONOMY SPEED		30 days
FRAME	SPACING		800 mm
WEB FRAME	SPACING		2400 mm
CREW	PERSONS		101 persons
PAX			172 persons
LSA	NUMBER		273 persons
TONNAGE	GROSS		8626
TONNAGE	NET		2588
FLAG			Cyprus



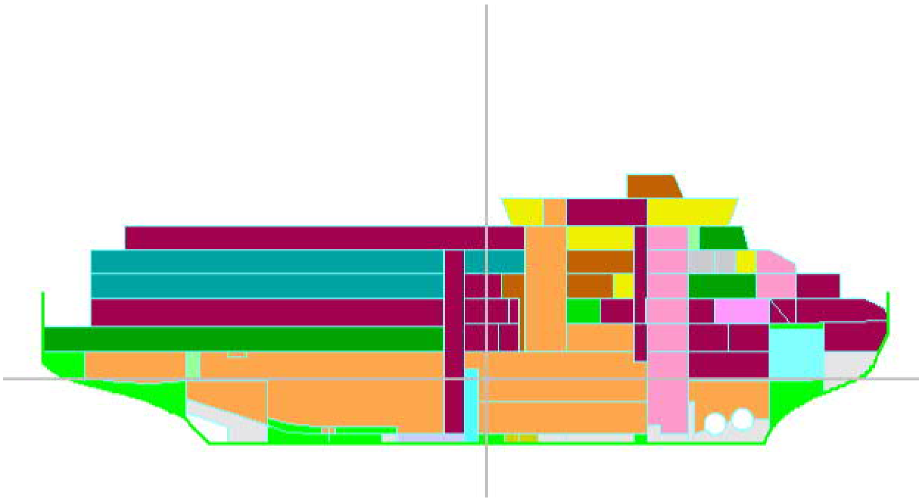

FORECASTLE DECK
(Deck 5)
MAIN DECK
(Deck 4)
TWEEN DECK
(Deck 3)
PLATFORM 5100
(Deck 2)
TANK TOP
(Deck 1)
DOUBLE BOTTOM (Deck 0)

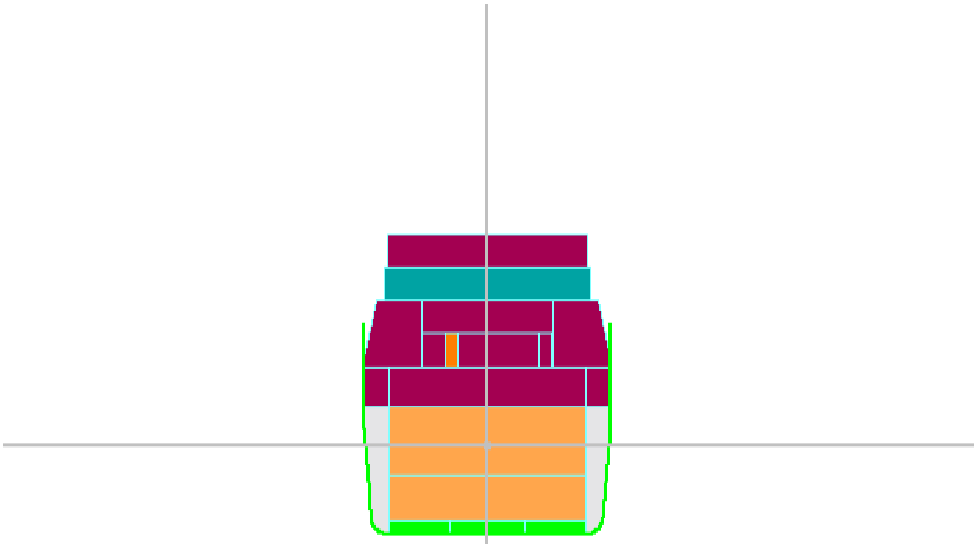
Appendix 2. Napa model (initial design)

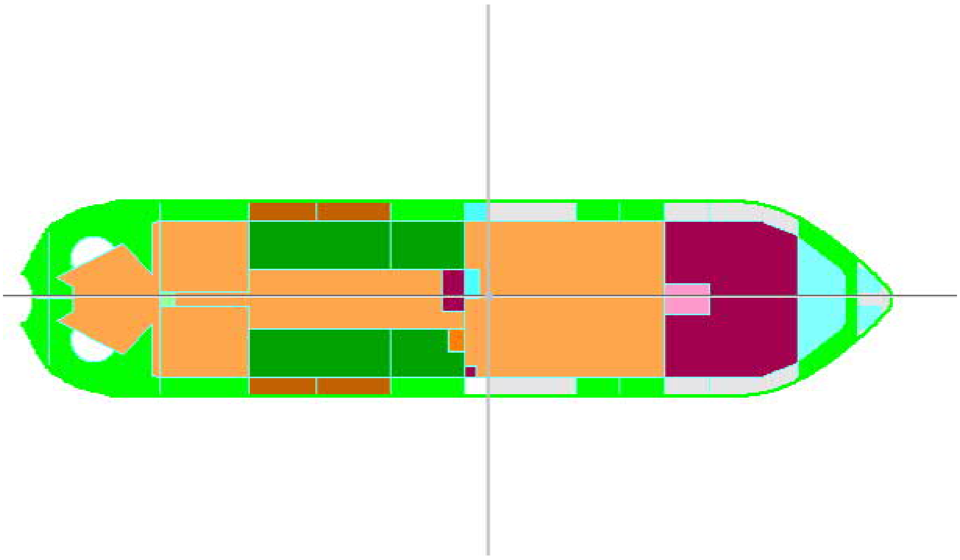
Ship Model



Geometry Model







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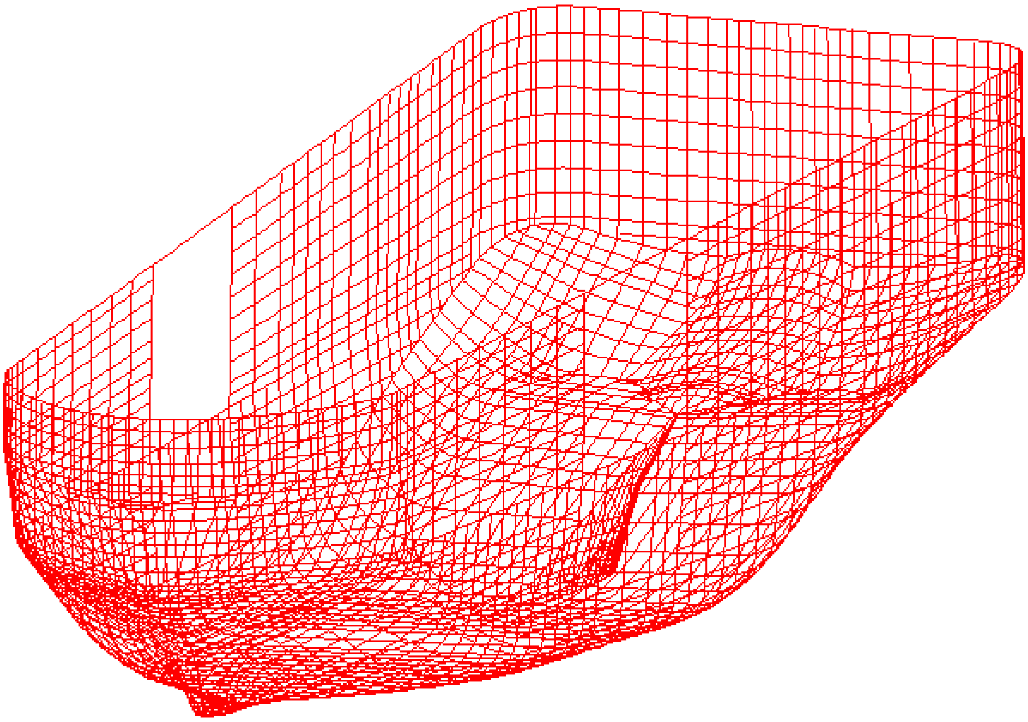
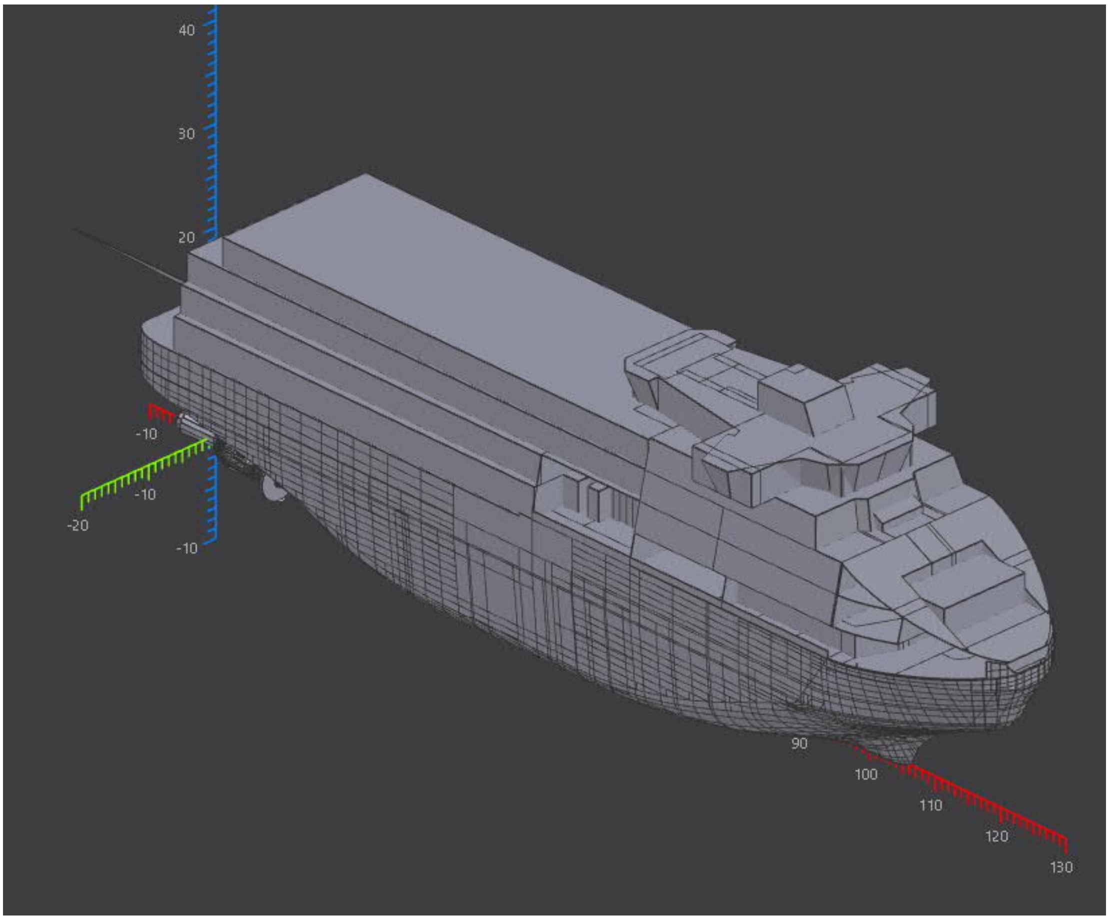


Napa designer



Compartments

	Name	DES	XMIN [m]	XMAX [m]	LCAP	RED [%]	VNET [m3]	WMAX [t]	VOLM [m3]	CGX [m]	CGY [m]	CGZ [m]
1	R010001	Ballast water	0.00	4.80	1.00	2.0	130.9	134.2	133.6	2.74	-4.59	9.50
2	R010002	Ballast water	0.00	4.80	1.00	2.0	130.9	134.2	133.6	2.74	4.59	9.50
3	R020001	Ballast Water	4.80	16.80	1.00	2.0	270.5	277.3	276.1	12.09	-6.15	7.33
4	R020002	Ballast Water	4.80	16.80	1.00	2.0	270.5	277.3	276.1	12.09	6.15	7.33
5	R040001	Ballast Water	26.40	33.60	1.00	2.0	85.0	87.1	86.7	29.84	4.47	0.86
6	R040002	Ballast water	26.40	33.60	1.00	2.0	85.0	87.1	86.7	29.84	-4.47	0.86
7	R050002	Ballast Water	33.60	40.00	1.00	2.0	48.2	49.4	49.2	36.80	0.00	0.60
8	R050003	Ballast Water	33.60	40.00	1.00	2.0	39.1	40.1	39.9	36.80	5.80	0.60
9	R050004	Ballast Water	33.60	40.00	1.00	2.0	39.1	40.1	39.9	36.80	-5.80	0.60
10	R070002	Ballast Water	49.60	54.40	1.00	2.0	30.1	30.8	30.7	52.32	-0.32	0.60
11	R070003	Ballast Water	49.60	58.40	1.00	2.0	53.8	55.2	54.9	54.00	5.80	0.60
12	R070004	Ballast Water	49.60	58.40	1.00	2.0	53.8	55.2	54.9	54.00	-5.80	0.60
13	R080001	Ballast water	61.60	69.60	1.00	2.0	60.2	60.2	61.4	65.60	0.00	0.60
14	R080002	Ballast water	61.60	71.20	1.00	2.0	124.3	127.4	126.8	66.41	0.00	0.64
15	R030001	Cofferdam	16.80	26.40	1.00	2.0	273.5	273.5	279.0	21.81	0.00	2.94
16	R050001	Dry tank	33.60	41.60	1.00	2.0	53.4	53.4	54.5	39.67	0.00	0.67
17	R090001	Dry Tank	71.20	76.00	1.00	2.0	279.7	279.7	285.5	73.47	0.00	4.56
18	R100001	Dry Tank	76.00	85.60	1.00	2.0	539.4	539.4	550.5	80.39	0.16	5.58
19	R110001	Ballast water	85.60	92.00	1.00	2.0	490.1	502.4	500.1	88.65	0.00	9.98
20	R120001	Dry tank	92.00	98.62	1.00	2.0	116.5	116.5	118.9	94.53	0.00	9.51
21	R060001	Treated Sewage Water	41.60	49.60	1.00	2.0	70.6	70.6	72.0	45.52	6.57	0.74
22	R060002	Treated Sewage Water	41.60	49.60	1.00	2.0	70.6	70.6	72.0	45.53	-6.57	0.74
23	R060003	Treated Sewage Water	41.60	49.60	1.00	2.0	60.2	60.2	61.4	45.60	0.00	0.60
24	R070005	Clean water tank	54.40	56.00	0.98	2.0	12.0	11.8	12.3	55.20	0.00	0.60
25	R070006	C.W. Drain	56.00	58.40	0.98	2.0	9.0	8.9	9.2	57.20	0.00	0.60
26	R.CH601	Ice Chest	49.60	51.20	1.00	2.0	44.7	45.8	45.6	50.40	1.60	4.45
27	R.CH701_2	Sea chest	49.60	52.00	1.00	2.0	36.7	37.6	37.4	50.80	9.31	4.90
28	R.CH702	Sea Chest	56.00	58.40	1.00	2.0	4.5	4.6	4.6	57.20	-2.40	0.60
29	R.CH703	Sea Chest	56.00	58.40	1.00	2.0	4.5	4.6	4.6	57.20	2.40	0.60
30	R.PODP	Pod geometry according to L507	5.10	13.64	1.00	2.0	32.4	32.4	33.1	9.05	4.71	2.97
31	R.PODS		5.10	13.64	1.00	2.0	32.4	32.4	33.1	9.05	-4.71	2.97
32	R020003	Void	7.27	12.10	1.00	2.0	34.1	34.1	34.8	9.69	-4.35	6.59
33	R020004	Void	7.27	12.10	1.00	2.0	34.1	34.1	34.8	9.69	4.35	6.59
34	R030002	Void	16.80	21.60	1.00	2.0	7.5	7.5	7.6	19.80	0.00	1.82
35	R070007	Void	49.60	52.00	1.00	2.0	47.7	47.7	48.7	50.80	-9.36	6.05
36	R100002	Void	80.40	81.20	1.00	2.0	0.6	0.6	0.6	80.79	2.92	2.28
37	R100003	Void	80.40	81.20	1.00	2.0	0.6	0.6	0.6	80.79	-2.92	2.28
38	R130001	Laundry	26.40	41.60	1.00	0.0	241.7	241.7	241.7	34.87	5.80	9.15
39	R130003	Store	26.40	41.60	1.00	0.0	241.7	241.7	241.7	34.87	-5.80	9.15
40	R130004	Provision	41.60	49.60	1.00	0.0	145.6	145.6	145.6	45.60	5.80	9.25
41	R130010	Provisions	41.60	49.60	1.00	0.0	145.6	145.6	145.6	45.60	-5.80	9.25
42	R030003	Cofferdam	16.80	26.40	1.00	0.0	1111.9	1111.9	1111.9	21.94	0.00	7.30
43	R140001	Ballast water	16.80	26.40	1.00	2.0	134.9	138.2	137.6	21.93	-9.42	7.59
44	R150001	Spare part room	18.40	49.60	1.00	0.0	1288.6	1288.6	1288.6	37.00	-0.08	6.54
45	R140002	Ballast water	16.80	26.40	1.00	2.0	134.9	138.2	137.6	21.93	9.42	7.59
46	R150002	Cabins	0.00	49.60	1.00	0.0	3119.7	3119.7	3119.7	24.72	-0.01	12.50
47	R150003	Restaurant area	5.60	49.60	1.00	0.0	2976.2	2976.2	2976.2	27.29	-0.01	15.65
48	R150004	Passenger cabins	5.60	49.60	1.00	0.0	2334.7	2334.7	2334.7	27.33	-0.01	18.70
49	R170001	Boat deck	49.60	61.60	1.00	0.0	301.2	301.2	301.2	55.77	-7.94	17.12
50	R170002	Public area	49.60	54.02	1.00	0.0	138.6	138.6	138.6	51.81	0.00	18.70
51	R150006	Passenger cabins	5.60	61.60	1.00	0.0	2578.4	2578.4	2578.4	31.93	-0.01	21.50
52	R150007	Public area	9.60	61.60	1.00	0.0	2324.7	2324.7	2324.7	34.07	0.00	24.30
53	R170003	Cafe	88.80	94.00	1.00	0.0	139.8	139.8	139.8	91.40	0.00	18.70
54	R070001	Dry Tank	52.00	61.60	1.00	2.0	444.5	444.5	453.6	57.25	0.00	5.29
55	R113002	Fresh water	85.60	92.00	1.00	0.0	217.1	217.1	217.1	88.36	3.04	10.69
56	R040101	MDO / Recovered Oil	26.40	33.60	0.98	2.0	184.5	155.5	188.2	30.09	-5.78	4.98
57	R040102	MDO / Recovered Oil	26.40	33.60	0.98	2.0	184.5	155.5	188.2	30.09	5.78	4.98
58	R040103	Roll reduction tank	26.40	32.80	1.00	2.0	234.0	239.8	238.7	29.68	0.00	3.53
59	R040106	Air canal	32.80	33.60	1.00	0.0	31.8	31.8	31.8	33.20	0.00	3.31
60	R050101	Roll reduction tank	34.40	41.60	1.00	2.0	279.1	286.1	284.8	37.98	0.00	3.32
61	R050102	MDO	33.60	41.60	0.98	2.0	212.0	178.7	216.3	37.60	5.77	4.90
62	R050103	MDO	33.60	41.60	0.98	2.0	212.1	178.7	216.4	37.60	-5.77	4.90
63	R050107	Air canal	33.60	34.40	1.00	0.0	31.9	31.9	31.9	34.00	0.00	3.31
64	R060101	Urea	41.60	48.00	0.98	2.0	199.0	167.7	203.1	44.80	5.77	4.45
65	R060102	MDO	41.60	48.00	0.98	2.0	199.0	167.7	203.1	44.80	-5.77	4.45
66	R060103	Ballast water	41.60	49.60	1.00	2.0	144.5	148.1	147.4	45.61	-9.39	6.58
67	R060104	Ballast water	41.60	49.60	1.00	2.0	144.5	148.1	147.4	45.61	9.39	6.58
68	R060107	ESC / Air Lock	47.20	49.60	1.00	0.0	238.2	238.2	238.2	48.40	0.91	12.05
69	R060108	Overflow	48.00	49.60	0.98	2.0	29.0	24.4	29.6	48.80	-4.40	5.05
70	R060109	Dispersant	48.00	49.60	0.98	2.0	23.7	23.2	24.2	48.80	4.40	4.35

71	R060110	HiPAP	48.00	49.60	1.00	0.0	27.8	27.8	27.8	48.81	-6.99	4.40
72	R060111	HiPAP	48.00	49.60	1.00	0.0	27.8	27.8	27.8	48.81	6.99	4.40
73	R070101	Pump Room	49.60	71.20	1.00	0.0	1173.0	1173.0	1173.0	59.55	0.03	3.16
74	R080101	Ballast / Drilling Water	61.60	66.40	1.00	2.0	96.9	99.3	98.9	64.04	-9.23	6.07
75	R080102	Ballast / Drilling Water	61.60	66.40	1.00	2.0	96.9	99.3	98.9	64.04	9.23	6.07
76	R080103	LO Ren. Tank	61.60	64.00	0.98	2.0	22.7	20.1	23.2	62.78	-6.88	3.32
77	R080104	TH Storage tank	66.40	68.40	0.98	2.0	14.6	12.8	14.9	67.38	-6.85	3.72
78	R080105	LO	61.60	63.20	0.98	2.0	15.5	15.1	15.8	62.39	6.89	3.29
79	R080106	Bilge Water Settling Tank	63.20	66.40	0.98	2.0	27.3	26.8	27.9	64.75	6.84	3.47
80	R080107	Bilge water holding	66.40	71.20	0.98	2.0	32.5	31.9	33.2	68.70	6.84	3.81
81	R080108	Sludge holding tank	68.40	71.20	0.98	2.0	18.0	17.6	18.3	69.77	-6.84	3.88
82	R080110	Th. Oil Drainage Tank	64.00	66.40	0.98	2.0	20.0	19.6	20.4	65.17	-6.84	3.51
83	R080111	Ballast / Drilling Water	66.40	71.20	1.00	2.0	103.7	106.3	105.8	68.81	-8.94	5.81
84	R080112	Ballast / Drilling Water	66.40	71.20	1.00	2.0	103.7	106.3	105.8	68.81	8.94	5.81
85	R090101	MDO Settling	71.20	76.00	0.98	2.0	82.5	69.6	84.2	73.54	-4.38	3.65
86	R090102	Bow thruster room	76.00	85.60	1.00	0.0	128.7	128.7	128.7	80.78	0.00	5.30
87	R090103	Stairs	71.20	76.00	1.00	0.0	145.4	145.4	145.4	73.66	0.00	6.25
88	R090104	MDO Settling	71.20	76.00	0.98	2.0	82.5	69.6	84.2	73.54	4.38	3.65
89	R070102	Escape	49.60	50.80	1.00	0.0	17.3	17.3	17.3	50.19	-7.62	5.55
90	R070201	Engine Room	49.60	71.20	1.00	0.0	2108.4	2108.4	2108.4	60.51	0.01	8.05
91	R090201	MDO Day	71.20	76.00	0.98	2.0	73.8	62.2	75.3	73.60	-5.01	6.26
92	R090202	MDO Day	71.20	76.00	0.98	2.0	70.0	59.0	71.4	73.71	4.88	6.25
93	R100201	MDO	76.00	84.80	0.98	2.0	110.8	93.4	113.0	79.88	-4.55	6.37
94	R100202	MDO	76.00	84.80	0.98	2.0	110.8	93.4	113.0	79.88	4.55	6.37
95	R090203	Boat FO	71.20	72.00	0.98	2.0	3.8	3.2	3.8	71.60	7.40	6.30
96	R020301	Propulsion Room	4.80	16.80	1.00	0.0	658.8	658.8	658.8	10.95	-0.02	9.28
97	R020309	Aft Capstan Recess	5.60	7.20	1.00	0.0	4.2	4.2	4.2	6.43	8.68	10.05
98	R020310	Aft Capstan Recess	5.60	7.20	1.00	0.0	4.2	4.2	4.2	6.43	-8.68	10.05
99	R020302	Ropes	11.20	12.00	1.00	0.0	3.7	3.7	3.7	11.60	8.80	9.55
100	R020303	Escape	10.00	11.20	1.00	0.0	4.8	4.8	4.8	10.60	8.80	9.75
101	R020304	Ropes	11.20	12.00	1.00	0.0	3.7	3.7	3.7	11.60	-8.80	9.55
102	R020306	Azipod Lub Oil	4.80	5.60	0.98	2.0	1.0	0.9	1.0	5.20	5.00	8.52
103	R020307	Azipod Hyd Oil	4.80	5.60	0.98	2.0	1.9	1.7	2.0	5.20	3.84	8.48
104	R020308	Escape	10.00	11.20	1.00	0.0	4.8	4.8	4.8	10.60	-8.80	9.75
105	R030301	Air lock	16.80	18.40	1.00	0.0	9.0	9.0	9.0	17.60	0.00	9.25
106	R040301	Roll Reduction Tank Valve Room	26.40	33.60	1.00	0.0	90.0	90.0	90.0	29.22	8.06	9.53
107	R040304	Roll Reduction Tank Valve Room	26.40	33.60	1.00	0.0	90.0	90.0	90.0	29.22	-8.06	9.53
108	R040305	Roll Reduction Tank Valve Room	33.60	41.60	1.00	0.0	61.1	61.1	61.1	37.60	9.49	9.27
108	R040305	Roll Reduction Tank Valve Room	33.60	41.60	1.00	0.0	61.1	61.1	61.1	37.60	9.49	9.27
109	R040306	Roll Reduction Tank Valve Room	33.60	41.60	1.00	0.0	61.1	61.1	61.1	37.60	-9.49	9.27
110	R070301	Void	49.60	52.00	1.00	2.0	10.9	10.9	11.2	50.80	9.51	9.95
111	R090301	Switchboard Room	71.20	85.60	1.00	0.0	782.2	782.2	782.2	78.52	0.00	9.22
112	R110301	Fresh water	85.60	92.00	1.00	0.0	217.1	217.1	217.1	88.36	-3.04	10.69
113	R120301	Chain lkr	92.00	94.40	1.00	0.0	40.3	40.3	40.3	93.11	1.91	10.72
114	R120302	Chain lkr	92.00	94.40	1.00	0.0	40.3	40.3	40.3	93.11	-1.91	10.72
115	R120401	Deck store	92.00	99.65	1.00	0.0	247.1	247.1	247.1	95.31	0.00	12.93
116	R070401	Oil Rec. Store & Gangway Watch	53.60	61.60	1.00	0.0	64.4	64.4	64.4	57.19	-7.12	12.62
117	R070402	Chemical Store	53.60	56.00	1.00	0.0	22.2	22.2	22.2	54.80	-4.20	12.65
118	R070403	Fire Locker	53.60	56.00	1.00	0.0	22.2	22.2	22.2	54.80	-1.40	12.65
119	R070404	Paint Store	53.60	56.00	1.00	0.0	22.2	22.2	22.2	54.80	1.40	12.65
120	R070405	Non Survivors	53.60	56.00	1.00	0.0	22.2	22.2	22.2	54.80	4.20	12.65
121	R070406	Oil Rec. Store & Gangway Watch	53.60	60.00	1.00	0.0	56.0	56.0	56.0	56.65	7.05	12.62
122	R070407	Machinery Air Intake	54.02	56.80	1.00	0.0	143.6	143.6	143.6	55.80	0.00	16.91
123	R070408	Casing	56.80	61.60	1.00	0.0	790.3	790.3	790.3	59.20	0.00	18.35
124	R080401	Welding	61.60	64.05	1.00	0.0	25.9	25.9	25.9	62.83	-4.00	12.65
125	R080402	Machinery Workshop	64.05	71.20	1.00	0.0	94.5	94.5	94.5	68.10	-3.44	12.65
126	R080403	Harbor DG Room	61.60	69.60	1.00	0.0	120.4	120.4	120.4	65.41	0.06	12.65
127	R080404	Lift	69.60	71.20	1.00	0.0	61.1	61.1	61.1	70.40	1.20	17.75
128	R080405	Lobby	61.60	63.20	1.00	0.0	16.9	16.9	16.9	62.40	4.00	12.65
129	R080406	Deck & Machinery Change Room	63.20	71.20	1.00	0.0	84.5	84.5	84.5	67.20	4.00	12.65
130	R090401	ECR	71.20	76.00	1.00	0.0	104.8	104.8	104.8	73.60	-7.31	12.65
131	R090402	Corridor	71.20	75.20	1.00	0.0	21.1	21.1	21.1	73.20	-3.20	12.65
132	R090403	Main Stairway Trunk	71.20	76.00	1.00	0.0	57.0	57.0	57.0	73.20	0.00	12.65
133	R090404	Corridor	71.20	76.00	1.00	0.0	25.3	25.3	25.3	73.60	3.20	12.65
134	R090405	Lobby / Reception	71.20	76.00	1.00	0.0	44.4	44.4	44.4	73.60	5.40	12.65
135	R090406	Sanitary Cabin	71.20	76.00	1.00	0.0	60.4	60.4	60.4	73.60	8.71	12.65
136	R100401	Sauna	76.00	80.80	1.00	0.0	101.7	101.7	101.7	78.40	-7.85	12.40
137	R100402	Sauna / Gym Change Room	75.20	80.80	1.00	0.0	42.2	42.2	42.2	78.12	-3.56	12.65
138	R100403	Sanitary Area	76.00	80.80	1.00	0.0	76.0	76.0	76.0	78.40	0.00	12.65
139	R100404	Recovery Area	76.00	85.60	1.00	0.0	373.9	373.9	373.9	82.71	0.36	12.65
140	R100405	Dispencary / Treatment Area	76.00	80.80	1.00	0.0	92.3	92.3	92.3	78.40	7.70	12.65
141	R090407	Pipes	73.60	74.40	1.00	0.0	14.1	14.1	14.1	74.00	-1.80	18.35
142	R090408	Pipes	73.60	74.40	1.00	0.0	14.1	14.1	14.1	74.00	1.80	18.35
143	R080407	Boat Deck	58.40	71.20	1.00	0.0	168.4	168.4	168.4	66.06	8.00	12.66
144	R080408	Boat Deck	58.40	71.20	1.00	0.0	168.4	168.4	168.4	66.06	-8.00	12.66
145	R010401	Safe Heaven Port	49.60	61.60	1.00	0.0	87.7	87.7	87.7	55.60	9.51	12.65
146	R010402	Safe Heaven Stb	49.60	61.60	1.00	0.0	87.7	87.7	87.7	55.60	-9.51	12.65
147	R060401	Covered Cargo Deck Area	49.61	53.60	1.00	0.0	221.4	221.4	221.4	51.60	0.00	12.65
148	R090409	Locker	74.40	76.00	1.00	0.0	6.3	6.3	6.3	75.20	-1.80	12.65
149	R090410	Locker	74.40	76.00	1.00	0.0	6.3	6.3	6.3	75.20	1.80	12.65
150	R070409	S.C. Lkr	60.00	61.60	1.00	0.0	8.4	8.4	8.4	60.80	7.60	12.65

151	R070501	EDG	49.60	54.80	1.00	0.0	129.6	129.6	129.6	52.02	-0.13	15.80
152	R070502	FRB Hangar	49.60	61.60	1.00	0.0	358.3	358.3	358.3	54.98	5.90	16.68
153	R080501	LSA Locker	61.60	65.60	1.00	0.0	38.4	38.4	38.4	63.60	-4.00	15.80
154	R080502	Incinerator	61.60	65.60	1.00	0.0	28.8	28.8	28.8	63.60	-1.20	15.80
155	R080503	Day Room / Library	61.60	71.20	1.00	0.0	149.8	149.8	149.8	66.09	2.92	15.80
156	R080504	Fire Locker	65.60	67.60	1.00	0.0	19.2	19.2	19.2	66.60	-4.00	15.80
157	R080505	Garbage	65.60	69.60	1.00	0.0	28.8	28.8	28.8	67.60	-1.20	15.80
158	R080506	Smoking	67.60	71.20	1.00	0.0	33.6	33.6	33.6	69.37	-4.04	15.80
159	R080507	Corridor	69.60	71.20	1.00	0.0	6.7	6.7	6.7	70.40	-1.90	15.80
160	R080508	AC Duct	69.60	71.20	1.00	0.0	26.8	26.8	26.8	70.39	-0.80	20.55
161	R080509	Life Boat Shelter	61.60	72.80	1.00	0.0	162.3	162.3	162.3	67.20	-8.02	15.77
162	R080510	Life Boat Shelter	61.60	72.80	1.00	0.0	162.3	162.3	162.3	67.20	8.02	15.77
163	R090501	Main Stairway Trunk	71.00	76.00	1.00	0.0	83.0	83.0	83.0	72.74	0.00	15.80
164	R090502	WC	72.80	76.00	1.00	0.0	15.8	15.8	15.8	74.56	2.56	15.80
165	R090503	Locker	74.40	76.00	1.00	0.0	5.8	5.8	5.8	75.20	-1.80	15.80
166	R100501	Mess	72.80	85.60	1.00	0.0	245.8	245.8	245.8	79.20	-5.60	15.80
167	R100502	Pantry	76.00	79.20	1.00	0.0	23.0	23.0	23.0	77.60	-1.20	15.80
168	R100503	Galley	76.00	85.60	1.00	0.0	115.2	115.2	115.2	81.44	0.24	15.80
169	R100504	Provision Stores	72.80	85.60	1.00	0.0	235.7	235.7	235.7	79.41	5.71	15.80
170	R110501	Deck store	85.60	88.80	1.00	0.0	37.3	37.3	37.3	86.95	6.12	15.80
171	R110502	Rope store	85.60	88.80	1.00	0.0	37.3	37.3	37.3	86.95	-6.12	15.80
172	R110503	Carpenter workshop	85.60	88.80	1.00	0.0	38.4	38.4	38.4	87.20	2.00	15.80
173	R110504	Boatswain workshop	85.60	88.80	1.00	0.0	30.9	30.9	30.9	87.08	-2.32	15.73
174	R110505	Front deck	72.80	99.65	1.00	0.0	614.5	614.5	614.5	89.69	-0.01	15.91
175	R070601	Stairs	56.80	61.60	1.00	0.0	28.2	28.2	28.2	59.20	6.65	18.70
176	R070503	EMG DO	51.60	54.00	0.98	2.0	7.1	5.9	7.2	52.80	3.10	15.80
177	R070504	Battery Room	51.60	54.80	1.00	0.0	19.2	19.2	19.2	53.20	4.60	15.80
178	R080602	AC-Room	61.60	67.20	1.00	0.0	75.3	75.3	75.3	64.40	0.00	18.70
179	R080603		61.60	85.60	1.00	0.0	402.4	402.4	402.4	73.60	6.80	18.67
180	R080604		61.60	85.60	1.00	0.0	402.4	402.4	402.4	73.60	-6.80	18.67
181	R080605	-	85.60	92.00	1.00	0.0	97.5	97.5	97.5	88.28	6.36	18.66
182	R080606	SuperNum. Publ. Space	85.60	92.00	1.00	0.0	99.2	99.2	99.2	88.26	-6.29	18.66
183	R080607		76.00	84.00	1.00	0.0	107.5	107.5	107.5	80.00	0.00	18.70
184	R080608		61.60	85.60	1.00	0.0	94.1	94.1	94.1	73.60	-3.10	18.70
185	R080609	-	61.60	88.80	1.00	0.0	119.2	119.2	119.2	76.25	2.65	18.70
186	R080610		71.20	76.00	1.00	0.0	48.4	48.4	48.4	73.20	0.00	18.70
187	R080611		74.40	76.00	1.00	0.0	5.4	5.4	5.4	75.20	1.80	18.70
188	R080612		74.40	76.00	1.00	0.0	5.4	5.4	5.4	75.20	-1.80	18.70
189	R080613	-	85.60	87.20	1.00	0.0	4.5	4.5	4.5	86.40	2.10	18.70
190	R080614	-	87.20	88.80	1.00	0.0	4.5	4.5	4.5	88.00	2.10	18.70
191	R080615		84.00	88.80	1.00	0.0	32.3	32.3	32.3	86.40	-1.20	18.70
192	R080616	Office	67.20	69.60	1.00	0.0	32.3	32.3	32.3	68.40	0.00	18.70
193	R080702		71.20	76.00	1.00	0.0	48.4	48.4	48.4	73.20	0.00	21.50
194	R080703		74.40	76.00	1.00	0.0	5.4	5.4	5.4	75.20	1.80	21.50
195	R080704		74.40	76.00	1.00	0.0	5.4	5.4	5.4	75.20	-1.80	21.50
196	R080705		61.60	85.60	1.00	0.0	359.2	359.2	359.2	73.60	6.48	21.47
197	R080706		61.60	85.60	1.00	0.0	359.2	359.2	359.2	73.60	-6.48	21.47
198	R080707	-	84.00	88.80	1.00	0.0	39.6	39.6	39.6	85.80	0.08	21.34
199	R080708		61.60	85.60	1.00	0.0	94.1	94.1	94.1	73.60	3.10	21.50
200	R080709		61.60	85.60	1.00	0.0	94.1	94.1	94.1	73.60	-3.10	21.50
201	R080710	AC-Room	61.60	71.20	1.00	0.0	118.3	118.3	118.3	66.04	-0.11	21.50
202	R080711	-	85.60	91.12	1.00	0.0	52.9	52.9	52.9	87.23	5.48	21.08
203	R080712	Laundry	76.00	79.20	1.00	0.0	43.0	43.0	43.0	77.60	0.00	21.50
204	R080713	Linen Store	79.20	81.60	1.00	0.0	18.8	18.8	18.8	80.40	1.00	21.50
205	R080714	Drying	79.20	81.60	1.00	0.0	13.4	13.4	13.4	80.40	-1.40	21.50
206	R080715		81.60	84.00	1.00	0.0	32.3	32.3	32.3	82.80	0.00	21.50
207	R080716	-	85.60	91.12	1.00	0.0	55.1	55.1	55.1	87.22	-5.32	21.08
208	R080802	Cabins	61.60	83.20	1.00	0.0	633.6	633.6	633.6	73.65	-0.20	24.26
209	R080803	Corridor	61.60	77.35	1.00	0.0	169.0	169.0	169.0	69.21	0.73	24.30
210	R080804	-	66.89	68.28	1.00	0.0	4.8	4.8	4.8	67.58	-1.78	24.30
211	R080805	Conference	61.60	69.60	1.00	0.0	90.3	90.3	90.3	65.74	0.34	24.30
212	R080806	-	71.20	76.00	1.00	0.0	48.4	48.4	48.4	73.20	0.00	24.30
213	R080807		74.40	76.00	1.00	0.0	5.4	5.4	5.4	75.20	-1.80	24.30
214	R080808	LO	61.60	62.62	1.00	0.0	6.0	6.0	6.0	62.11	-2.75	24.30
215	R080809		74.40	76.00	1.00	0.0	5.4	5.4	5.4	75.20	1.80	24.30
216	R080901	Wheelhouse	54.02	81.96	1.00	0.0	879.0	879.0	879.0	70.08	0.00	27.40
217	R080902	Casing	58.80	61.60	1.00	0.0	43.7	43.7	43.7	60.20	0.00	27.33
218	R080903	-	64.00	69.60	1.00	0.0	23.7	23.7	23.7	66.80	-1.75	27.33
219	R080904	-	69.60	71.20	1.00	0.0	6.8	6.8	6.8	70.40	-1.75	27.33
220	R080905		61.60	71.20	1.00	0.0	103.7	103.7	103.7	65.51	0.30	27.33
221	R080906	Lift Machinery	68.80	71.20	1.00	0.0	15.6	15.6	15.6	70.00	1.40	27.33
222	R081001	AC-Room	68.80	75.60	1.00	0.0	78.0	78.0	78.0	72.08	-0.11	30.30
223	R081002	Battery	68.80	70.00	1.00	0.0	5.4	5.4	5.4	69.40	1.60	30.35

Appendix 3. Openings

ID	DES	WT
A_BW3S	TANK AIRPIPE	WEATHERTIGHT
A_BW5P	TANK AIRPIPE	WEATHERTIGHT
A_BW5S	TANK AIRPIPE	WEATHERTIGHT
A_HWB1P	TANK AIRPIPE	WEATHERTIGHT
A_HWB1S	TANK AIRPIPE	WEATHERTIGHT
A_HWB2P	TANK AIRPIPE	WEATHERTIGHT
A_HWB2S	TANK AIRPIPE	WEATHERTIGHT
A_BW6P	TANK AIRPIPE	WEATHERTIGHT
A_BW6S	TANK AIRPIPE	WEATHERTIGHT
A_DT4P	TANK AIRPIPE	WEATHERTIGHT
A_DT4S	TANK AIRPIPE	WEATHERTIGHT
A_BW12P	TANK AIRPIPE	WEATHERTIGHT
A_BW12S	TANK AIRPIPE	WEATHERTIGHT
A_CFWP	TANK AIRPIPE	WEATHERTIGHT
A_CFWS	TANK AIRPIPE	WEATHERTIGHT
A_FW	TANK AIRPIPE	WEATHERTIGHT
A_DT7	TANK AIRPIPE	WEATHERTIGHT
A_DT8	TANK AIRPIPE	WEATHERTIGHT
A_DT5P	TANK AIRPIPE	WEATHERTIGHT
A_DT5S	TANK AIRPIPE	WEATHERTIGHT
A_DT6P	TANK AIRPIPE	WEATHERTIGHT
A_DT6S	TANK AIRPIPE	WEATHERTIGHT
CROSS1	CROSS / DOWNFLOODING DEVICE R070004 R070003	UNPROTECTED
CROSS1#2		
CROSS2	CROSS / DOWNFLOODING DEVICE R060002 R060001	UNPROTECTED
CROSS2#2		
CROSS3	CROSS / DOWNFLOODING DEVICE R050004 R050003	UNPROTECTED
CROSS3#2		
CROSS4	CROSS / DOWNFLOODING DEVICE R040002 R040001	UNPROTECTED
CROSS4#2		
E13P	VERTICAL ESCAPE #13	WEATHERTIGHT
E13P_CURVE	VERTICAL ESCAPE #13	WEATHERTIGHT
E13S	VERTICAL ESCAPE #13	WEATHERTIGHT
E13S_CURVE	VERTICAL ESCAPE #13	WEATHERTIGHT
E63S	VERTICAL ESCAPE #63	WEATHERTIGHT
E63S_CURVE	VERTICAL ESCAPE #63	WEATHERTIGHT
E106	VERTICAL ESCAPE #106	WEATHERTIGHT
E106_CURVE	VERTICAL ESCAPE #106	WEATHERTIGHT
D78P	DOOR TO LOBBY #78	WEATHERTIGHT
D79S	TO WELDING ROOM.	WEATHERTIGHT
D85S	TO MACH WORKSHOP	WEATHERTIGHT
D89P	DOOR #89 P-SIDE	WEATHERTIGHT
D89.2P	DOOR TO LOBBY #89	WEATHERTIGHT
D89S	DOOR #89 S-SIDE	WEATHERTIGHT
D97P	DOOR TO PROV STORE	WEATHERTIGHT
D111P	DOOR TO DECK STORE	WEATHERTIGHT
D111S	DOOR TO ROPE STORE	WEATHERTIGHT

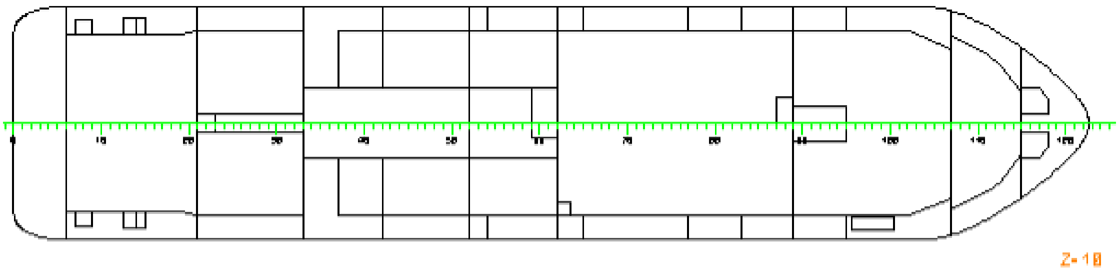
ID	OTYPE	GEOMOBJ	FR	REFX m	REFY m
A_BW3S			#37+0.400	30.000	-10.300
A_BW5P			#43+0.400	34.800	8.600
A_BW5S			#43+0.400	34.800	-8.600
A_HWB1P			#34	27.200	10.100
A_HWB1S			#40-0.200	31.800	-10.100
A_HWB2P			#51+0.300	41.100	10.100
A_HWB2S			#51+0.300	41.100	-10.100
A_BW6P			#61+0.250	49.050	10.300
A_BW6S			#60+0.400	48.400	-10.300
A_DT4P			#75	60.000	10.300
A_DT4S			#74+0.400	59.600	-10.300
A_BW12P			#85+0.400	68.400	10.300

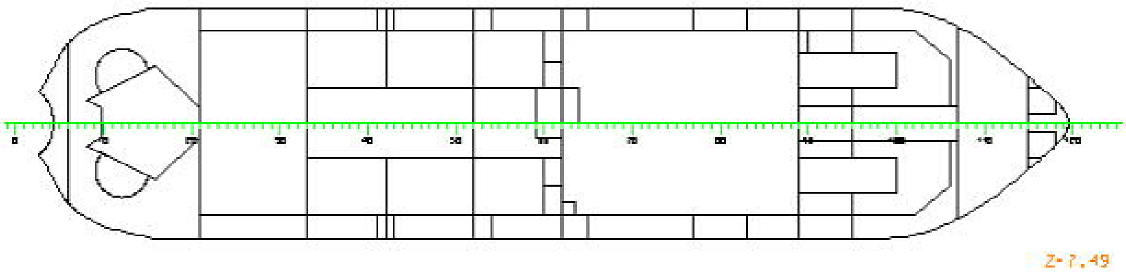
ID	OTYPE	GEOMOBJ	FR	REFX	REFY
				m	m
A_BW12S			#83+0.400	66.800	-10.300
A_CFWP			#111+0.300	89.100	3.600
A_CFWS			#111+0.300	89.100	-3.600
A_FW			#111+0.300	89.100	0.850
A_DT7			#111+0.300	89.100	-4.650
A_DT8			#116+0.400	93.200	-0.560
A_DT5P			#93	74.400	10.300
A_DT5S			#93	74.400	-10.300
A_DT6P			#104	83.200	10.300
A_DT6S			#104	83.200	-10.300
CROSS1	PIPE		#67+0.400	54.000	-5.800
CROSS1#2	PIPE		#67+0.400	54.000	5.800
CROSS2	PIPE		#57-0.073	45.527	-6.570
CROSS2#2	PIPE		#57-0.077	45.523	6.567
CROSS3	PIPE		#46	36.800	-5.800
CROSS3#2	PIPE		#46	36.800	5.800
CROSS4	PIPE		#37+0.282	29.882	-6.122
CROSS4#2	PIPE		#37+0.282	29.882	6.122
E13P	VERTICAL ESCAPE		#13-0.210	10.190	9.620
E13P_CURVE	VERTICAL ESCAPE	C.ESC13P	0	0.000	0.000
E13S	VERTICAL ESCAPE		#13-0.210	10.190	-9.620
E13S_CURVE	VERTICAL ESCAPE	C.ESC13S	0	0.000	0.000
E63S	VERTICAL ESCAPE		#63-0.200	50.200	-8.400
E63S_CURVE	VERTICAL ESCAPE	C.ESC63S	0	0.000	0.000
E106	VERTICAL ESCAPE		#106	84.800	1.100
E106_CURVE	VERTICAL ESCAPE	C.ESC106	0	0.000	0.000
D78P			#78	62.400	5.600
D79S			#79	63.200	-5.600
D85S			#85	68.000	-5.600
D89P			#89	71.200	6.600
D89.2P			#89	71.200	3.600
D89S			#89	71.200	-3.600
D97P			#97+0.400	78.000	8.800
D111P			#111	88.800	5.100
D111S			#111	88.800	-5.100

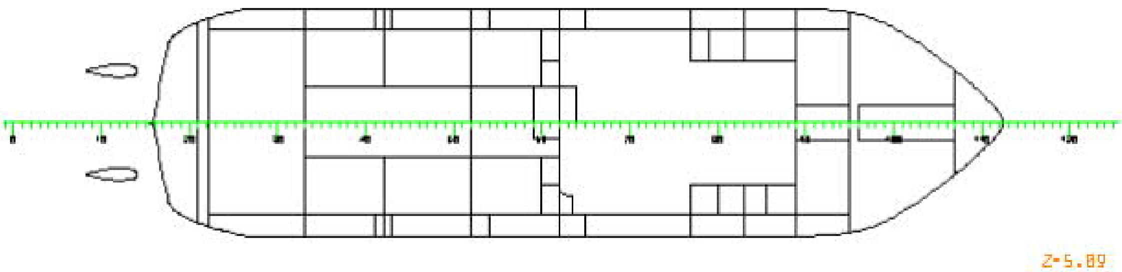
Appendix 4. Versions A and B, case 3

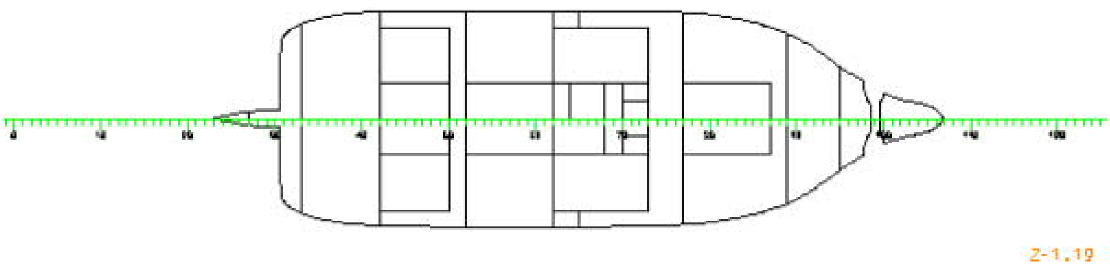
Versio A

A = 0.70534









Versio B

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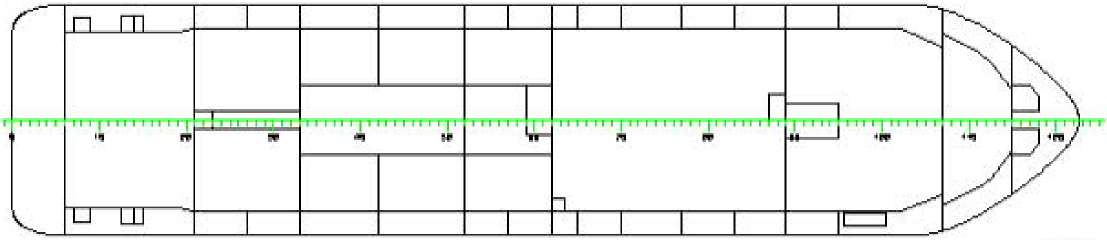

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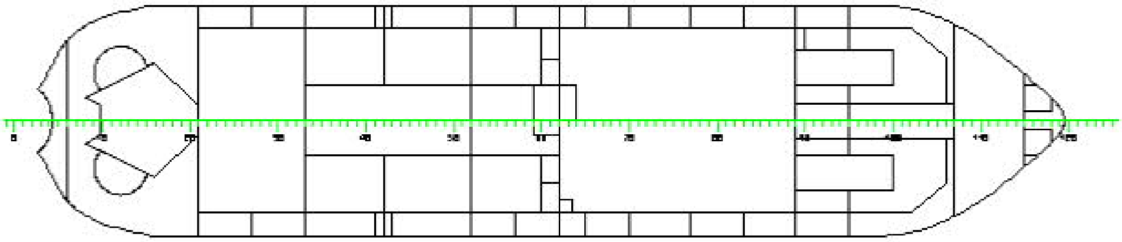

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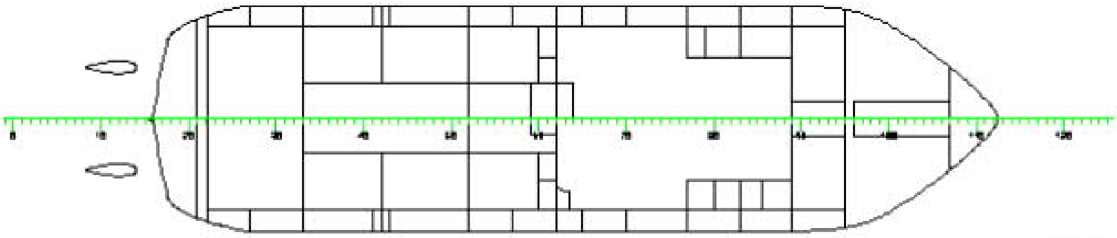

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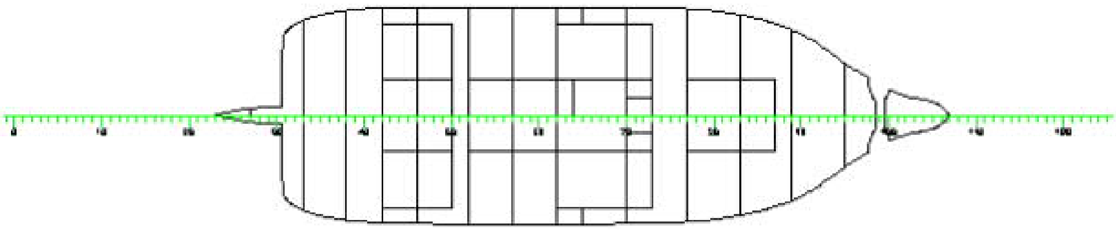

Z=1.19

Appendix 5. A-indices

Case 1: Initial design

```
PROBABILISTIC DAMAGE STABILITY
--------------------------------
DAMAGES                  W*P*V*S

--------------------------------
1-ZONE DAMAGES           0.29591
2-ZONE DAMAGES           0.22626
3-ZONE DAMAGES           0.08766
4-ZONE DAMAGES           0.04504
5-ZONE DAMAGES           0.01740
6-ZONE DAMAGES           0.01769
7-ZONE DAMAGES           0.00269
--------------------------------
A-INDEX TOTAL            0.69265
--------------------------------


THE SUM OF WCOEF*PFAC*VFAC EQUALS 0.980626
OPTIMUM EQUALS 1.00000
```

Case 2: U-tanks

```
PROBABILISTIC DAMAGE STABILITY
--------------------------------
DAMAGES                  W*P*V*S

--------------------------------
1-ZONE DAMAGES           0.29599
2-ZONE DAMAGES           0.22442
3-ZONE DAMAGES           0.08884
4-ZONE DAMAGES           0.04493
5-ZONE DAMAGES           0.02090
6-ZONE DAMAGES           0.01589
7-ZONE DAMAGES           0.00335
--------------------------------
A-INDEX TOTAL            0.69433
--------------------------------


THE SUM OF WCOEF*PFAC*VFAC EQUALS 0.979606
OPTIMUM EQUALS 1.00000
```

Case 3: Denser transversal subdivision

Version A

```
PROBABILISTIC DAMAGE STABILITY
--------------------------------
DAMAGES                    W*P*V*S

--------------------------------
1-ZONE DAMAGES             0.29666
2-ZONE DAMAGES             0.22965
3-ZONE DAMAGES             0.09124
4-ZONE DAMAGES             0.04734
5-ZONE DAMAGES             0.01859
6-ZONE DAMAGES             0.01865
7-ZONE DAMAGES             0.00322
--------------------------------
A-INDEX TOTAL              0.70534
--------------------------------


THE SUM OF WCOEF*PFAC*VFAC EQUALS 0.980626
OPTIMUM EQUALS 1.00000
```

Version B

```
PROBABILISTIC DAMAGE STABILITY
--------------------------------
DAMAGES                    W*P*V*S

--------------------------------
1-ZONE DAMAGES             0.26593
2-ZONE DAMAGES             0.24065
3-ZONE DAMAGES             0.10597
4-ZONE DAMAGES             0.05506
5-ZONE DAMAGES             0.02506
6-ZONE DAMAGES             0.02110
7-ZONE DAMAGES             0.00495
--------------------------------
A-INDEX TOTAL              0.71873
--------------------------------


THE SUM OF WCOEF*PFAC*VFAC EQUALS 0.966344
OPTIMUM EQUALS 1.00000
```

Main version

```
PROBABILISTIC DAMAGE STABILITY
---------------------------------
DAMAGES                    W*P*V*S

---------------------------------
1-ZONE DAMAGES             0.27096
2-ZONE DAMAGES             0.23947
3-ZONE DAMAGES             0.10688
4-ZONE DAMAGES             0.05741
5-ZONE DAMAGES             0.02505
6-ZONE DAMAGES             0.02119
7-ZONE DAMAGES             0.00501
---------------------------------
A-INDEX TOTAL              0.72598
---------------------------------


THE SUM OF WCOEF*PFAC*VFAC EQUALS 0.966344
OPTIMUM EQUALS 1.00000
```

Case 4: Cross-flooding

```
PROBABILISTIC DAMAGE STABILITY
---------------------------------
DAMAGES                    W*P*V*S

---------------------------------
1-ZONE DAMAGES             0.30159
2-ZONE DAMAGES             0.23521
3-ZONE DAMAGES             0.08813
4-ZONE DAMAGES             0.04772
5-ZONE DAMAGES             0.02011
6-ZONE DAMAGES             0.01839
7-ZONE DAMAGES             0.00306
---------------------------------
A-INDEX TOTAL              0.71420
---------------------------------


THE SUM OF WCOEF*PFAC*VFAC EQUALS 0.980626
OPTIMUM EQUALS 1.00000
```

Case 5: Final design

```
PROBABILISTIC DAMAGE STABILITY
--------------------------------
DAMAGES                  W*P*V*S

--------------------------------
1-ZONE DAMAGES           0.28391
2-ZONE DAMAGES           0.24994
3-ZONE DAMAGES           0.09539
4-ZONE DAMAGES           0.05136
5-ZONE DAMAGES           0.02179
6-ZONE DAMAGES           0.01868
7-ZONE DAMAGES           0.00401
--------------------------------
A-INDEX TOTAL            0.72508
--------------------------------


THE SUM OF WCOEF*PFAC*VFAC EQUALS 0.976153
OPTIMUM EQUALS 1.00000
```

Appendix 6. Rendered image